

Stellar Yields and Chemical Evolution I: Abundance Ratios and Delayed Mixing in the Solar Neighbourhood

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ABSTRACT

We analyse two recent computations of type II supernova nucleosynthesis by Woosley & Weaver (1995, hereafter WW95) and Thielemann, Nomoto, & Hashimoto (1996, hereafter TNH96), focusing on the ability to reproduce the observed $[\text{Mg}/\text{Fe}]$ -ratios in various galaxy types. We show that the yields of oxygen and total metallicity are in good agreement. However, TNH96-models produce more magnesium in the intermediate and less iron in the upper mass range of type II supernovae than WW95-models. To investigate the significance of these discrepancies for chemical evolution, we calculate *Simple Stellar Population*-yields for both sets of models and different IMF slopes. We conclude that the Mg-yields of WW95 do not suffice to explain the $[\text{Mg}/\text{Fe}]$ overabundance neither in giant elliptical galaxies and bulges nor in metal-poor stars in the solar neighbourhood and the galactic halo. Calculating the chemical evolution in the solar neighbourhood according to the standard infall-model (e.g. Matteucci & Greggio 1986; Timmes, Woosley, & Weaver 1995; Yoshii, Tsujimoto, & Nomoto 1995), we find that using WW95 and TNH96 nucleosynthesis, the solar magnesium abundance is underestimated by 29 and 7 per cent, respectively.

We include the relaxation of the instantaneous *mixing* approximation in chemical evolution models by splitting the gas component into two different phases. In additional simulations of the chemical evolution in the solar neighbourhood, we discuss various timescales for the mixing of the stellar ejecta with the interstellar medium. We find that a delay of the order of 10^8 years leads to a better fit of the observational data in the $[\text{Mg}/\text{Fe}]$ - $[\text{Fe}/\text{H}]$ diagram without destroying the agreement with solar element abundances and the age-metallicity relation.

Key words: stars: stellar yields – stars: type Ia and type II supernovae – stars: Simple Stellar Population – galaxies: element abundances – galaxies: solar neighbourhood – chemical evolution: instantaneous mixing approximation

1 INTRODUCTION

Understanding the formation and evolution of galaxies is difficult because it involves many different processes that are coupled in a complex way. In order to simulate a scenario properly, one has to consider the dynamics of stars, gas and dark matter as well as star formation, the interaction with the interstellar medium (ISM), and chemical enrichment (Hensler & Burkert 1990). Since this problem includes many unknown parameters, it is more effective to decouple

various processes and to closely inspect observational constraints which are relevant to the different parameters.

Chemical evolution models constrain star formation histories, supernova rates, and abundances in the ISM, in the stars, and in the intracluster medium (ICM). Thus, trying to reproduce element abundances in chemical simulations already puts significant constraints on galaxy formation without considering complicated dynamical aspects. Hence, in the present stage it is more effective to decouple the dynamical and the chemical approach.

Different timescales for the duration of the star forming phase cause different abundance ratios in the stars and in the ISM. In short phases of star formation short-living, massive stars govern the enrichment of the ISM. Thus, in those formation scenarios the abundance ratios reflect the type

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II supernova (SN II) production (Hashimoto, Iwamoto, & Nomoto 1993).

In order to obtain the various element abundances in the solar neighbourhood, a modest and continuous star formation rate (SFR) is necessary (Matteucci et al. 1989). In the standard models (e.g. Matteucci & Greggio 1986; Timmes, Woosley, & Weaver 1995; Tsujimoto et al. 1995), this kind of star formation history is obtained with infall of primordial gas on a timescale of several Gyr and an SFR which depends on the gas density via the Schmidt-law (Schmidt 1959; Schmidt 1963). In this scenario, the disk of the Galaxy is assumed to form out of slowly accreting gas. Since star formation occurs over a long timescale of 10^{10} yr, the chemical evolution is noticeably influenced by SN Ia.

In bulges and elliptical galaxies, $[\alpha/\text{Fe}]$ -ratios seem to be enhanced with respect to solar abundances (Peletier 1989; Worthey, Faber, & Gonzalez 1992; Davies, Sadler, & Peletier 1993; McWilliam & Rich 1994). Since the α -elements are mainly produced in massive stars experiencing SN II explosions (Woosley 1986), and iron is substantially contributed by type Ia supernovae (SN Ia), the chemical history of the light dominating component of the stellar population in bulges and ellipticals must be dominated by massive stars. In chemical evolution models, this can be realized by either (Worthey et al. 1992; Matteucci 1994)

- (i) a flat IMF or
- (ii) a short phase of star formation or
- (iii) a low fraction of close binary systems experiencing SN Ia.

Chemical evolution models have to constrain and quantify these different possibilities.

Although in the pure chemical approach the number of input parameters is already reduced, there are still plenty of uncertainties in the calculations. Typical input parameters are the shape and slope of the initial mass function (IMF), the SFR, the infall rate and the fraction of close binary systems producing iron via type Ia supernovae. However, chemical evolution is also very sensitive to the adopted stellar yields, especially of SN II (see also Gibson 1997). Thus, besides the parameters above, chemical evolution models should always take into account different stellar nucleosynthesis prescriptions, which are strongly affected by uncertainties of stellar evolution models (Thielemann, Nomoto, & Hashimoto 1996).

In this paper, we compare two recently published nucleosynthesis calculations for SN II by:

- (i) Woosley & Weaver (1995), hereafter WW95
- (ii) Thielemann et al. (1996) and Nomoto et al. (1997)[§], hereafter TNH96.

We focus on the question, if the considered sets of models are able to explain an important observed feature of galaxy formation: the $[\text{Mg}/\text{Fe}]$ overabundance. There is a broad consensus that metal-poor halo stars in our Galaxy have magnesium enhanced abundance ratios (Gratton & Snenen 1988; Magain 1989; Edvardsson et al. 1993; Axer, Fuhrmann, & Gehren 1994; Axer, Fuhrmann, & Gehren 1995; Fuhrmann,

Axer, & Gehren 1995). The exact value of the enhancement is still debatable, but it seems to converge to 0.3 – 0.4 dex (Truran & Burkert 1993; Gehren 1995). This observation can be easily understood taking into account that metal-poor stars form in the early stages of the galaxy formation, when the enrichment due to SN II is dominating chemical evolution. However, we will show that there are still unresolved problems caused by uncertainties in stellar nucleosynthesis.

As already noted, in elliptical galaxies there are strong indications from spectra in the visual light that there is a magnesium overabundance of at least 0.2 dex in nuclei of these galaxies (Worthey et al. 1992; Weiss, Peletier, & Matteucci 1995). However, while the halo in the solar neighbourhood has low metallicities ($-3 \leq [\text{Fe}/\text{H}] \leq -1$), the stars which dominate the visual light in the nuclei of ellipticals have solar or super-solar Z (Greggio 1997). Therefore, the $[\text{Mg}/\text{Fe}]$ overabundance is realized at both low and high Z in two considerably different systems. While a detailed inspection of element abundances in elliptical galaxies will be the subject of a forthcoming paper, in this work we concentrate on the chemical evolution of the solar neighbourhood using WW95 and TNH96 SN II yields.

In order to calibrate our code, we use the same approach as in the most common chemical evolution models (Matteucci & Greggio 1986; Timmes, Woosley, & Weaver 1995) for the solar neighbourhood, performing the calculation for both sets of nucleosynthesis prescriptions. Taking finite stellar lifetimes into account, the classical numerical models relax the instantaneous *recycling* approximation, but usually assume the stellar ejecta to mix instantaneously with the ISM (Tinsley 1980). Only few attempts have been made in the literature to relax the instantaneous *mixing* approximation in numerical models of chemical evolution (see discussion in Timmes et al. 1995). We present a modification of the basic equations (Tinsley 1980) splitting the gaseous mass into two different phases, one including the stellar ejecta and the second being cool and well mixed. The mixing process is characterized by a gas flow from the first, inactive to the active, star forming gas phase. We additionally present the results of simulations considering this modification.

In section 2 we summarize the most important aspects of chemical evolution, while in section 3 we discuss stellar yields from SN II explosions, comparing WW95 and TNH96. We analyse their influence on chemical evolution by calculating the SSP-yields of various elements in section 4. In section 5 we present our model for the chemical evolution in the solar neighbourhood. In the conclusion we summarize the main results.

2 GENERALITIES ON CHEMICAL EVOLUTION

2.1 The basic equations

Non-primordial elements develop in a cycle of birth and death of stars. These form out of the ISM, process elements, and eject them during the late stages of their evolution in the form of stellar winds, planetary nebulae (PN), or supernovae (SN Ia and SN II), depending on their main sequence mass m . The formation of stars and the re-ejection of gas can be described by the following phenomenological equa-

[§] In this paper, the results of Thielemann et al. (1996) are extended on a larger mass range.

tions (Tinsley 1980):

$$dM_{\text{tot}}/dt = f \quad (1)$$

$$dM_s/dt = \psi - E \quad (2)$$

$$dM_g/dt = -\psi + E + f \quad (3)$$

The total baryonic mass $M_{\text{tot}} = M_s + M_g$ is governed by infall or outflow f of material, being either primordial or enriched gas. The total stellar mass M_s is *increasing* according to the SFR ψ and *decreasing* due to re-ejection E of gas. The total gaseous mass M_g behaves exactly contrary to M_s with the additional component of in-falling or out-flowing gas f .

The ejection rate E is obtained by integrating the ejected mass fraction $(1 - w_m)$, folded with the SFR and the normalized IMF ϕ , from the turnoff mass m_t to the maximum stellar mass m_{max} . Here, w_m denotes the mass fraction of the remnant.

$$E(t) = \int_{m_t}^{m_{\text{max}}} (1 - w_m) \psi(t - \tau_m) \phi(m) dm \quad (4)$$

The quantity τ_m is the stellar lifetime of a star with mass m . In the instantaneous *recycling* approximation, τ_m is assumed to be negligible in comparison to the time t . This approximation is relaxed in numerical simulations as well as in our evolution code. This must not be confused with the instantaneous *mixing* approximation (IMA) which is assumed in most chemical evolution models (Matteucci & Greggio 1986; Timmes et al. 1995; Tsujimoto et al. 1995; Pagel & Tautvaisiene 1995). In section 5, we also relax this assumption and take a delay in the mixing of the stellar ejecta into account.

Parallel to equation 3, the mass production of the element i in the ISM ($X_i M_g$) is expressed in the equation below:

$$d(X_i M_g)/dt = -X_i \psi + E_i + X_{i,f} f \quad (5)$$

Here, X_i is the abundance of element i in the ISM, $X_{i,f}$ is the abundance of element i in the in-falling or out-flowing gas. The element ejection rate E_i is obtained by integrating the ejected mass fraction Q_{im} (including both initial abundance and newly produced material) of the element i , again folded with the SFR and IMF over the appropriate mass range, equivalent to equation 4:

$$E_i(t) = \int_{m_t}^{m_{\text{max}}} Q_{im} \psi(t - \tau_m) \phi(m) dm \quad (6)$$

Equations 3 and 5 can be combined to describe the progression of the abundance X_i of element i in the ISM.

$$M_g dX_i/dt = E_i - X_i E + (X_{i,f} - X_i) f \quad (7)$$

The key value in this equation is the stellar yield Q_{im} hidden in the element ejection rate E_i . We neglect stellar winds during the evolution, and assume that the stars enrich the ISM at the time when they die. Depending on their initial mass, they either experience a SN II explosion ($m > 8 M_\odot$) or become a white dwarf blowing off their envelopes ($m < 8 M_\odot$). Elements heavier than oxygen are mainly processed in supernovae. A substantial fraction of iron is contributed by SN Ia. Adopting the description of the supernova rates from Greggio & Renzini (1983), the element ejection rate integrated over the total mass range can be described with the following equation as in Matteucci &

Greggio (1986) and Timmes et al. (1995):

$$\begin{aligned} E_i(t) = & \int_{16}^{m_{\text{max}}} Q_{im}^{\text{SNII}} \psi(t - \tau_m) \phi(m) dm \\ & + (1 - A) \int_8^{16} Q_{im}^{\text{SNII}} \psi(t - \tau_m) \phi(m) dm \\ & + (1 - A) \int_3^8 Q_{im}^{\text{PN}} \psi(t - \tau_m) \phi(m) dm \\ & + A \int_3^{16} \phi(m) dm \int_{\mu_{\text{inf}}}^{0.5} 24\mu^2 Q_{im}^{\text{SN Ia}} \psi(t - \tau_{\mu m}) d\mu \\ & + \int_1^3 Q_{im}^{\text{PN}} \psi(t - \tau_m) \phi(m) dm \end{aligned} \quad (8)$$

In this equation, the enrichment due to stars in the mass range $3 - 16 M_\odot$ is splitted into a contribution by type II supernovae (Q^{SNII}) plus planetary nebulae (Q^{PN}), due to single stars, and type Ia supernovae ($Q^{\text{SN Ia}}$), assumed to be the end product of close binary evolution. In the formulation of Greggio & Renzini (1983) μ is the ratio between the mass of the secondary and the total mass m of the system. The maximum fraction of the secondary is 0.5 by definition, while the minimum mass μ_{inf} is dependent on the turnoff as defined in the following equation (Greggio & Renzini 1983):

$$\mu_{\text{inf}} \equiv \text{MAX} [m_t/m, (m - 8)/m] \quad (9)$$

One has to integrate the distribution of the secondary component $f(\mu) \sim \mu^2$, folded with the yield (independent of the mass of the system) and the SFR over the appropriate mass range. The clock of the SN Ia explosion is given by the lifetime of the secondary $\tau_{\mu m}$, whose mass can be as low as $0.8 M_\odot$ (Greggio & Renzini 1983). Thus, the enrichment due to SN Ia is substantially delayed with respect to SN II. The degree of influence by SN Ia highly depends on the fraction A of close binaries, which is a free parameter in chemical evolution. Greggio & Renzini (1983) calibrate A on the ratio between the current type II to type Ia supernova rates in the Galaxy.

It should be noticed that equation 8 is not completely consistent, since m refers to the mass of single and binary stars. Nevertheless, as long as the parameter A is small (as in our case) type Ia events can be regarded as a small perturbation. Hence, equation 8 is an acceptable approximation, and it allows us to describe the delayed release of iron from SN Ia.

In these terms, the rates of type II and Ia supernovae can be described by the following equations:

$$\begin{aligned} R_{\text{II}} = & \int_{16}^{m_{\text{max}}} \psi(t - \tau_m) \frac{\phi(m)}{m} dm \\ & + (1 - A) \int_8^{16} \psi(t - \tau_m) \frac{\phi(m)}{m} dm \end{aligned} \quad (10)$$

$$R_{\text{Ia}} = A \int_3^{16} \frac{\phi(m)}{m} dm \int_{\mu_{\text{inf}}}^{0.5} 24\mu^2 \psi(t - \tau_{\mu m}) d\mu \quad (11)$$

2.2 Parameter constraints

In spite of the several unknown parameters (IMF slope x , SFR as a function of time, stellar yields), the following arguments show how they can be constrained by different observational information, step by step. This is useful for the

interpretation of the results from chemical evolution calculations.

Assuming the instantaneous *recycling* approximation, one can take ψ out of the integral in eqn. 4. For large t , the residual integral expressing the returned fraction R_x depends strongly on the IMF slope x but only marginally on turnoff mass (and then time). Equation 2 can then be written as:

$$dM_s/dt \approx \psi(1 - R_x) \quad (12)$$

The integrated solution demonstrates that the final total mass of stars depends on the *time-average* star formation rate $\bar{\psi}$ and the IMF slope.

$$M_s \approx M_{s,0} + (1 - R_x) \int_{t_0}^t \psi(t') dt', \quad (13)$$

where the subscript zero refers to the initial conditions. Similar considerations show that the final mass of gas in the ISM depends on a mean SFR $\bar{\psi}$, a mean infall rate \bar{f} and the IMF slope.

$$M_g \approx M_{g,0} - (1 - R_x) \int_{t_0}^t \psi(t') dt' + \int_{t_0}^t f(t') dt' \quad (14)$$

Now we need an approximation to pin down x . For this purpose, we consider the element abundances at the time t . The above approximation applied to equation 5 leads to

$$X_i M_g \approx X_{i,0} M_{g,0} - (X_i - X_{i,0}) \bar{\psi} (t - t_0) + R_{ix} \bar{\psi} (t - t_0) + (X_{i,f} - X_{i,f,0}) \bar{f} (t - t_0) \quad (15)$$

with R_{ix} as the returned mass fraction of element i mostly dependent on the IMF slope and the stellar yield. If we consider an element whose stellar yield is well known, we get a constraint on x (with known abundance of the in-falling gas), for a given minimum mass of the stellar population m_{\min} .

To summarize, the stellar and gaseous mass at the current epoch and the abundance of a specific element whose yield is relatively certain constrain $\bar{\psi}$, \bar{f} and x . We can then draw conclusions on the nucleosynthesis of other elements, whose stellar yields are relatively uncertain. In other words, from chemical evolution of galaxies one can get a constraint on the stellar evolution models. This is a convincing example how tight these two disciplines are coupled. Since the approximation $\tau_m \ll t$ is especially valid for elements produced mainly by type II supernovae, we will use this strategy in section 5 to fix the IMF slope with the element oxygen and constrain the necessary magnesium yield in SN II.

2.3 The initial mass function

The IMF is as usual assumed to be a declining function of mass, according to a power law: $\phi \sim m^{-x}$. Since the IMF is usually normalized *by mass*, the actual amount of mass created in one generation of stars is controlled by the SFR ψ .

$$\int_{m_{\min}}^{m_{\max}} \phi(m) dm = 1 \quad (16)$$

In these terms, the slope $x = 1.35$ corresponds to the Salpeter-value (Salpeter 1955).

Table 1. The most abundant elements ejected in a type Ia supernova. In the calculations, Nomoto et al. (1984) assume accreting white dwarfs in close binary systems to be the progenitors of SN Ia events. The data refer to the W7 model, the values are given in M_{\odot} . The numbers show that the ejecta of SN Ia are clearly dominated by ^{56}Fe .

| | | | | | |
|------------------|--------|------------------|--------|------------------|--------|
| ^{12}C | 3.2e-2 | ^{28}Si | 1.6e-1 | ^{56}Fe | 6.1e-1 |
| ^{16}O | 1.4e-1 | ^{32}S | 8.2e-2 | ^{57}Fe | 1.1e-2 |
| ^{20}Ne | 1.1e-2 | ^{36}Ar | 2.2e-2 | ^{58}Ni | 6.1e-2 |
| ^{24}Mg | 2.3e-2 | ^{40}Ca | 4.1e-2 | ^{60}Ni | 1.1e-2 |

To avoid uncertain extrapolations of the stellar yields to the high mass end, we have adopted $m_{\max} = 40 M_{\odot}$ which is the maximum mass for which WW95-models are computed. TNH96 do give the yields for a $70 M_{\odot}$ -star. For the comparison between the two sets of models we keep m_{\max} fixed at $40 M_{\odot}$. The effect of adopting $m_{\max} = 70 M_{\odot}$ is explored in section 4.5 and 5.3.

The lower cutoff of one generation of stars is assumed to be $m_{\min} = 0.1 M_{\odot}$. The higher the minimum mass, the larger is the fraction of massive stars, thus more metals are produced. Abundance ratios, however, are not affected by the choice of m_{\min} .

Alternative formulations of the IMF with different slopes at different mass ranges exist in the literature (e.g. Scalo 1986; Kroupa, Tout, & Gilmore 1995; Gould, Bahcall, & Flynn 1997). However, in order to keep the number of free parameters low, we have decided to fix $m_{\min} = 0.1 M_{\odot}$ and use one specific slope x for the whole mass range. The value of x , instead, is treated as a free parameter.

3 STELLAR YIELDS AND NUCLEOSYNTHESIS

3.1 PN and SN Ia

In our calculations, we use the results in Renzini & Voli (1981) for the enrichment due to intermediate mass single stars ($1 \leq m \leq 8 M_{\odot}$). In particular we select the models with $\alpha = 1.5$, $\eta = 0.33$.

Type Ia SNe are assumed to occur in close binary systems (Whelan & Iben 1973). In this model, the explosion is caused by a carbon-deflagration of the material accreting degenerate white dwarf (Hansen & Wheeler 1969; Nomoto 1980; Weaver & Woosley 1980; Nomoto 1981). We adopt the results of the nucleosynthesis from the classical W7-model by Nomoto, Thielemann, & Yokoi (1984).

Low mass stars, in the range $1 M_{\odot}$ to $8 M_{\odot}$, do not contribute to the enrichment of O, Mg and Fe (Renzini & Voli 1981). Type Ia supernovae produce significantly more iron than oxygen or magnesium as can be seen in table 1. One can see that ^{56}Fe is clearly dominating the ejecta. It follows that SN II must be the main contributor to the α -elements enrichment.

3.2 SN II

As mentioned in the introduction, we use two sets of models for the enrichment due to type II supernova explosions: WW95 and TNH96.

The calculation of the SN II yields is affected by many uncertainties (see WW95, TNH96 and references therein). Elements lighter than iron like carbon, oxygen, and magnesium are mainly produced during the evolutionary stages of the star *before* the explosion (Weaver & Woosley 1995). Thus, their abundances in the SN II-ejecta are highly dependent on stellar evolution, especially on the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ -rate during He-burning and the treatment of convection. Both, a higher $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ -rate and the inclusion of semi-convection lead to a smaller production of carbon and carbon-burning products (TNH96).

The iron produced in hydrostatic silicon burning during the pre-supernova evolution forms the core of the star, which represents the minimum mass of the remnant. Depending on the position of the mass-cut and the fraction of mass falling back, the remnant mass can be higher (Nomoto & Hashimoto 1988; Hashimoto et al. 1993; Weaver & Woosley 1993). The total amount of iron in the ejecta is exclusively produced during the explosion. More precisely, most of the explosively generated ^{56}Ni decays to ^{56}Fe . Thus, the theoretical iron yield of a SN II does not directly depend on parameters of stellar evolution, but on the simulation of the explosion itself.

Table 2 shows the important differences between the two sets. WW95 specify models A, B and C. In model B, the explosion energies are enhanced by a factor ~ 1.5 in stars with $m \geq 30 M_{\odot}$, in model C by a factor ~ 2 in stars with $m \geq 35 M_{\odot}$, both with respect to model A. TNH96 enhance the explosion energy for $m \geq 25 M_{\odot}$ by a factor of 1.5 with respect to the lower masses, as well. Hence, their models correspond best to model B in WW95. In the following, if not otherwise specified, the considered WW95-models are model B.

We discuss the differences in the yields of H, He, O, Mg, Fe and total ejected metals Z_{ej} as functions of the main sequence mass of the star $m (M_{\odot})$. TNH96 evolve helium cores of mass m_{α} , adopting the relation between m and m_{α} from Sugimoto & Nomoto (1980). The total ejected mass of a certain element is then given by the calculated yield from the evolution of m_{α} plus the original element abundance in the envelope $m - m_{\alpha}$. Since TNH96 consider solar initial metallicity, for the discussion of the yields we assume the element abundances in the envelope to be solar. We use the solar element abundances from Anders & Grevesse (1989), meteoritic values. It should be mentioned that the $70 M_{\odot}$ -star of the TNH96-results is not shown in the plots, but the relative yields are given in the captions.

3.2.1 Ejected mass and hydrogen

The left panels in figure 1 show the total ejected masses. Models A (WW95) are characterized by the fall-back of envelope material in the high mass range, an effect less pronounced in models B and virtually absent in models C. Except for the case $Z = 0$, the dependence on metallicity seems unimportant. The ejected masses in the WW95 and TNH96 models are very similar.

Conversely, the hydrogen yield (figure 1, right panels) is clearly dependent on the initial metallicity of the star, especially at the high mass end. Furthermore, for $m \gtrsim 20 M_{\odot}$ the H-yield given by TNH96 is larger than that in WW95-models

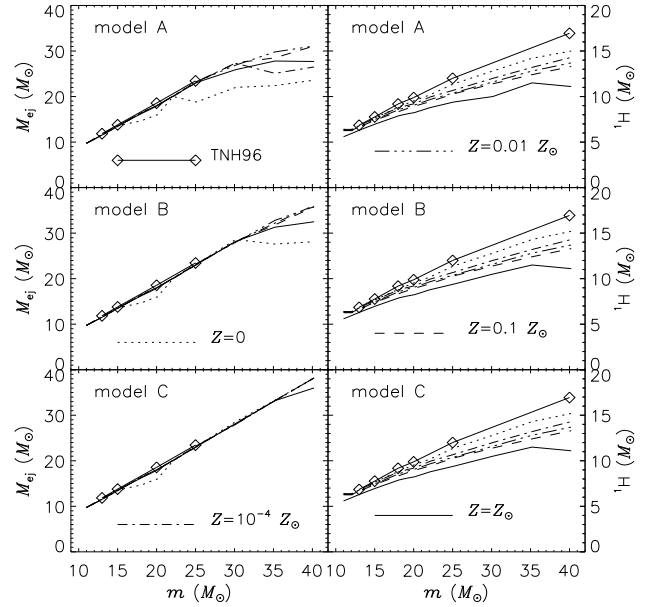


Figure 1. Total ejected mass (left panel) and hydrogen yield (right panel) of SN II as a function of initial stellar mass (M_{\odot}). In each panel, one of the different line styles is defined, indicating the five different initial metallicities assumed in WW95. The diamonds refer to the results of TNH96 (Z_{\odot}). The second and third row show the results for enhanced explosion energy in high mass stars in the calculations of WW95. The yields include initial and newly synthesized material. The hydrogen yield in the WW95-models shows a clear dependence on metallicity for high mass stars.

Table 3. SN II ^4He yields according to WW95 (Z_{\odot} , model B) and TNH96. The numbers are given in M_{\odot} . Since Nomoto et al. (1997) do not give He-yields, the considered (smaller) mass grid is taken from Thielemann et al. (1996).

| | 13 M_{\odot} | 15 M_{\odot} | 20 M_{\odot} | 25 M_{\odot} |
|-------|----------------|----------------|----------------|----------------|
| WW95 | 4.51 | 5.24 | 6.72 | 8.64 |
| TNH96 | 4.13 | 4.86 | 5.95 | 6.63 |

Both prescriptions basically agree in the value of $m_{\text{H}} + m_{\text{He}}$. Table 3 shows that the higher value for m_{H} corresponds to a lower helium yield in TNH96.

The difference in hydrogen (and then helium) yields comes from two causes: a different m_{α} - m relation at He ignition and the fact that TNH96 neglect the H-shell burning occurring after He ignition. In this respect we notice that in WW95 models, the m_{α} of a $25 M_{\odot}$ star is $9.21 M_{\odot}$, $1.21 M_{\odot}$ larger than that adopted by TNH96 for the same initial mass, on the basis of the m_{α} - m relation by Sugimoto & Nomoto (1980). The He-yield of this star is $2 M_{\odot}$ larger than in TNH96 models, reflecting the He-production due to the H-burning shell. A fair comparison between the predictions of the two sets of models should be done at constant m_{α} . However, since we lack the m_{α} -values for WW95 models for masses other than $25 M_{\odot}$, we proceed comparing the elements production for the same initial mass.

Table 2. The main differences in the SN II nucleosynthesis prescriptions of WW95 and TNH96. Models B and C in WW95 refer to enhanced explosion energies in high mass stars by a factor of 1.5 and 2, respectively. TNH96 do not specify different models, but also enhance the explosion energy in high mass stars by a factor of 1.5. Differences in stellar evolution ($^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ -rate, convection theory) mainly affect the nucleosynthesis of intermediate elements lighter than iron. The yield of iron itself is highly dependent on the explosion.

| | WW95 | TNH96 |
|--|--|--|
| $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ | $1.7 \times$ Caughlan & Fowler (1988), 74 per cent of TNH96 | Caughlan et al. (1985) |
| convection | Ledoux criterion, modification for semi-convection | Schwarzschild criterion, convective shells have greater extend |
| explosion energy | 1.2×10^{51} erg (model A) model B: $E_B \approx 1.5 \times E_A$ for $m \geq 30 M_\odot$ model C: $E_C \approx 2 \times E_A$ for $m \geq 35 M_\odot$ | 1.0×10^{51} erg $E = 1.5 \times 10^{51}$ erg for $m \geq 25 M_\odot$ |
| explosion mechanism | piston situated at the Y_e discontinuity | deposition of energy |
| neutrinos | nucleosynthesis caused by the flood of neutrinos | neutrino process <i>not</i> included |
| mass grid | 11, 12, 13, 15, 18, 19, 20, 22, 25, 30, 35, 40 M_\odot | 13, 15, 18, 20, 25, 40, 70 M_\odot |
| initial metallicity | grid of 5 different Z_{in} | only solar Z_{in} |
| stellar evolution | entire stars | helium cores |

3.2.2 Oxygen and metallicity

The yield of oxygen and total ejected mass of all elements heavier than helium (Z) are plotted in figure 2. The figure shows that Z is clearly dominated by oxygen. Both depend only weakly on initial metallicity except for the $Z_{\text{in}} = 0$ case. The results of WW95 and TNH96 are similar, except that TNH96 produce more oxygen in the higher mass range. This can be understood in terms of the higher $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ -rate in the TNH96 models. It is worth noting that the large difference in the yields of high mass stars may also result from the fact that WW95 consider fall back of material, whereas TNH96 do not. The O-yield of TNH96 increases rapidly with mass, the WW95-yields, instead, seem to saturate. This discrepancy already indicates that there is a huge uncertainty concerning the stellar yields of high mass stars ($m > 40 M_\odot$).

At the lower mass range ($m \leq 20 M_\odot$), WW95 yields tend to be slightly larger for the same metallicity (Z_\odot), possibly because of the larger m_α . However, the similarity of the results of the two sets of models suggests that the uncertainty in the oxygen yield from SN II is small.

3.2.3 Magnesium and iron

Both, WW95 and TNH96 produce a Mg-yield with a rapid rise in a certain mass range at $M \approx 18 M_\odot$ for TNH96 and at $M \approx 23 M_\odot$ for WW95. As a consequence, in the mass range 18–25 M_\odot , the Mg yield of TNH96 is larger by about a factor of 3–5. We will briefly investigate the origin of this discrepancy, which, as we will show, is very significant in the context of chemical evolution.

^{24}Mg is mainly produced during hydrostatic carbon-burning. Thus, table 4 gives the yields of ^{12}C , ^{16}O and of the main carbon-burning products ^{20}Ne , ^{23}Na , ^{24}Mg (Arnett & Thielemann 1985). ^{24}Mg is produced in the following reaction (Arnett & Thielemann 1985):

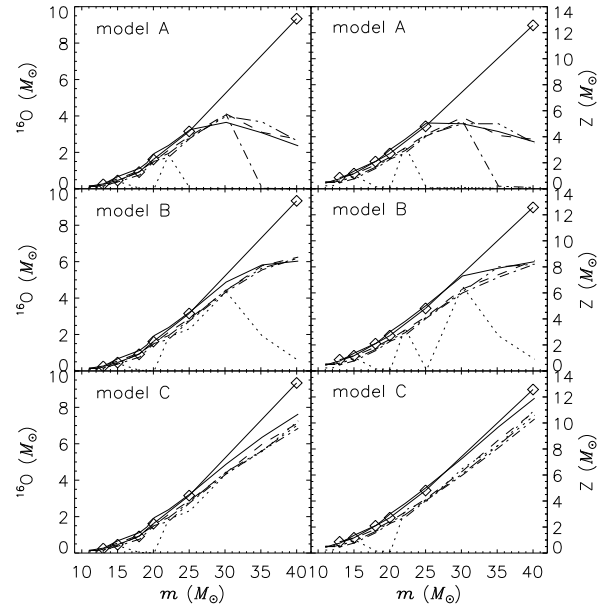
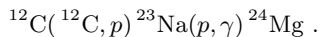


Figure 2. Oxygen yield (left panel) and ejected metallicity (right panel) of SN II as a function of initial stellar mass (M_\odot). The different linestyles and symbols are explained in figure 1. The yields include initial and newly synthesized material. The figure demonstrates that oxygen is clearly dominating the total metallicity of the ejecta. The dependence on initial metallicity of the star seems negligible (except for $Z_{\text{in}} = 0$). The oxygen yield of the 70 M_\odot -star according to TNH96 is $\sim 22 M_\odot$.

Hence, the model producing more carbon should also produce more magnesium. Table 4 shows, that the carbon yields are systematically higher in WW95 for all stellar masses. This is reasonable when taking into account the larger helium cores[¶] and the lower $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ -rate of WW95.

[¶] Carbon is a helium-burning product.

Table 4. SN II yields of the elements C, O, and the main carbon-burning products; comparison of WW95 (Z_{\odot} , model B) and TNH96. The numbers are given in units of M_{\odot} . The TNH96 numbers consist of the given yield from helium core evolution plus the initial abundance (solar) of the envelope (see text). In spite of the systematically larger ^{12}C -yield, WW95 give less ^{24}Mg in most of the stars, although magnesium is a carbon-burning product. Due to WW95, this pattern is caused by the different convection theories (see text).

| | | 13 M_{\odot} | 15 M_{\odot} | 18 M_{\odot} | 20 M_{\odot} | 25 M_{\odot} | 40 M_{\odot} |
|------------------|-------|----------------|----------------|----------------|----------------|----------------|----------------|
| ^{12}C | WW95 | 1.14(−1) | 1.61(−1) | 2.48(−1) | 2.13(−1) | 3.22(−1) | 3.63(−1) |
| | TNH96 | 3.21(−2) | 1.16(−1) | 2.04(−1) | 1.56(−1) | 2.00(−1) | 2.21(−1) |
| ^{16}O | WW95 | 2.72(−1) | 6.80(−1) | 1.13 | 1.94 | 3.25 | 6.03 |
| | TNH96 | 2.44(−1) | 4.60(−1) | 9.17(−1) | 1.61 | 3.15 | 9.34 |
| ^{20}Ne | WW95 | 4.46(−2) | 1.11(−1) | 2.77(−1) | 1.05(−1) | 3.94(−1) | 1.24 |
| | TNH96 | 3.82(−2) | 3.86(−2) | 1.82(−1) | 2.52(−1) | 6.22(−1) | 6.97(−1) |
| ^{23}Na | WW95 | 1.08(−3) | 3.42(−3) | 9.99(−3) | 1.53(−3) | 1.08(−2) | 3.68(−2) |
| | TNH96 | 1.05(−3) | 5.20(−4) | 7.68(−3) | 1.62(−3) | 1.87(−2) | 2.45(−2) |
| ^{24}Mg | WW95 | 1.64(−2) | 2.67(−2) | 5.52(−2) | 3.13(−2) | 1.06(−1) | 2.30(−1) |
| | TNH96 | 1.42(−2) | 3.73(−2) | 4.29(−2) | 1.54(−1) | 1.68(−1) | 3.66(−1) |

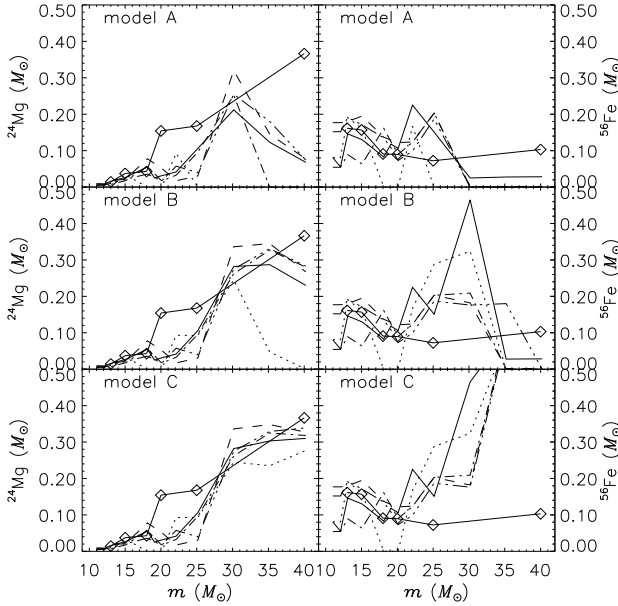


Figure 3. Magnesium yield (left panel) and iron yield (right panel) of SN II as a function of initial stellar mass (M_{\odot}). The different linestyles and symbols are explained in figure 1. The yields include initial and newly synthesized material. The dependence of both, the Mg- and Fe-yields, on initial metallicity is not very clear. TNH96 and WW95 agree very well in the Mg- and Fe-yields for low mass stars. The magnesium and iron yields of the 70 M_{\odot} -star according to TNH96 are $\sim 0.8 M_{\odot}$ and $\sim 0.1 M_{\odot}$, respectively.

However, for the yields of ^{20}Ne , ^{23}Na and ^{24}Mg this is not the case for all masses. In general, for low mass stars ($m \leq 18 M_{\odot}$) the yields of the carbon-burning products ^{20}Ne and ^{23}Na are higher in WW95 models as well. With the exception of the 40 M_{\odot} -star, the higher masses exactly inverse this pattern. The yield of ^{24}Mg behaves similar, but the effect is much stronger with the largest discrepancy for the 20 M_{\odot} -star. WW95 argue that the larger extent of the convective shells in the TNH96-models (Schwarzschild cri-

Table 5. Theoretical and observed ejected ^{56}Ni (M_{\odot}) in the SN II events SN1993J (14 M_{\odot} ; Arnett et al. 1989) and SN1987A (20 M_{\odot} ; Baron et al. 1995; Nomoto et al. 1995). The observational data are compared with the theoretical results of TNH96 and WW95. Both nucleosynthesis prescriptions are in agreement with observation.

| m_* (M_{\odot}) | observation | WW95 (Z_{\odot}) | TNH96 |
|-----------------------|------------------|----------------------|---------------|
| 14 \pm 1 | 0.100 \pm 0.02 | 0.133 – 0.115 | 0.153 – 0.130 |
| 20 | 0.075 \pm 0.01 | 0.088 | 0.074 |

terion) is responsible for the above behaviour. Since the observations of magnesium overabundance can be better explained with high Mg-yields in SN II (see following sections), this could be interpreted as an argument in favour of the Schwarzschild criterion in convection theory.

Similar to the O-yields, the Mg-yields of WW95 seem to saturate or even decline for increasing mass above 40 M_{\odot} , due to re-implosion. According to the TNH96 calculations, instead, a huge amount of magnesium is ejected by high mass stars.

Figure 3 shows, that the iron yield declines for masses between 13 M_{\odot} and 20 M_{\odot} in both sets of models. The iron yields in the lower mass range are very similar, both models match the observational constraints at 14 M_{\odot} (SN1993J; e.g. Baron, Hauschildt, & Young 1995; Nomoto, Iwamoto, & Suzuki 1995) and 20 M_{\odot} (SN1987A; e.g. Arnett et al. 1989). Table 5 shows that both groups can reproduce the observed ^{56}Ni of the supernova events, which is dominating the iron yield. Thus, in the lower mass range, TNH96 and WW95 basically agree in the Fe-yield.

However, WW95 produce significantly more iron than TNH96 in stars of $m \geq 25 M_{\odot}$, especially in model B and C. Thus, mainly this mass range will be responsible for discrepancies in the Fe-yields of the total mass range of SN II (SSP-yields, see section 4).

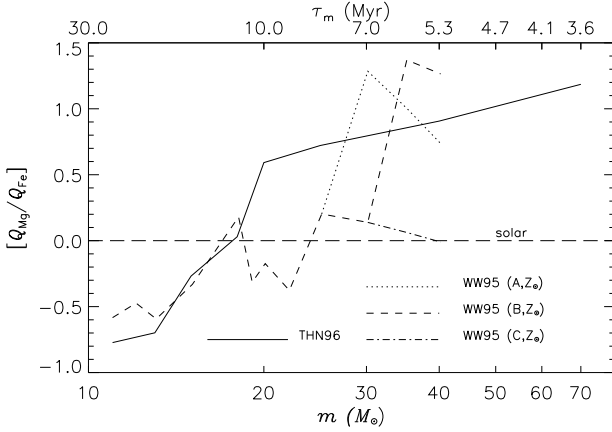


Figure 4. Abundance ratio of magnesium to iron in the ejecta of type II SNe as a function of initial stellar mass. The values are normalized on solar values and plotted on a logarithmic scale. The WW95-models of solar initial metallicity are considered. The upper x-axis denotes the lifetime τ_m of the star with mass m (Schaller et al. 1992). Mainly stars in the upper mass range contribute to super-solar [Mg/Fe]-ratios.

3.3 IMF-weighted yields

For the discussion of chemical evolution, it is more meaningful to consider stellar yields weighted by the IMF. Normalized on the SN II yield of the whole mass range, these values give the relative contribution of a $1 M_\odot$ interval to the total SN II yield. To show the role of various mass intervals to the enrichment of a certain element, we plot the IMF weighted yields of the elements oxygen, magnesium, iron, and metallicity for different IMF slopes and both nucleosynthesis models WW95 and TNH96. In more detail, we plot the following quantity:

$$\frac{dQ_{im}}{dm} = \frac{Q_{im} \times \phi(m)}{\int_{11}^{40} Q_{im} \times \phi(m) dm} \quad (17)$$

The figures are given in the appendix A. Summarizing the plots, we obtain the following results:

- (i) There is no specific mass range dominating the O- and Z-enrichment significantly for all considered IMF slopes.
- (ii) The IMF weighted Mg-yield is slightly peaked at $30 M_\odot$ (WW95) and $20 M_\odot$ (TNH96), but again these masses do not dominate the SSP-yield significantly.
- (iii) The Fe-enrichment due to SN II, instead, is clearly governed by stars of $m \leq 20 M_\odot$.

Altogether, the plots demonstrate the increasing weight of the higher mass range with decreasing IMF slope x .

3.4 The ratio [Mg/Fe]

In figure 4, we plot the abundance ratio [Mg/Fe] produced in WW95 (Z_\odot) and TNH96 as a function of stellar mass. The figure shows that the ratio of magnesium to iron is basically increasing with mass. In the intermediate mass range, the overabundance in TNH96 models exceeds the results of WW95 significantly. The maximum overabundance in TNH96 is reached in the most massive star ($m = 70 M_\odot$), whereas Mg/Fe of the WW95-models peaks at $m = 35 M_\odot$.

According to WW95, a magnesium overabundance is only produced in stars with $m \gtrsim 25 M_\odot$ (except for the small peak at $m = 18 M_\odot$). Thus, in the first ~ 10 Myr, when the turnoff is above $20 M_\odot$ (see upper x-axis in figure 4), these stars will enrich the ISM with highly magnesium overabundant ejecta. But already 30 Myr after the beginning of star formation, the turnoff of $10 M_\odot$ is reached and the whole SN II generation of stars is contributing to the enrichment. Thus, the key value for the discussion of chemical evolution is the SSP-yield.

4 SSP-YIELDS

We calculated SSP-yields of the elements oxygen, magnesium, iron in the mass range of type II SNe for different IMF slopes and both sets of SN II nucleosynthesis. The tables in the appendix B give the abundances of the considered elements in the ejecta of SN II explosions of one SSP ($m_{\max} = 40 M_\odot$). The basic conclusion for the discussion of the yields are:

- (i) The highest [Mg/Fe]-ratio in WW95 is produced in model B assuming an initial metallicity of $Z = 10^{-4} Z_\odot$. This ratio is lowest for models C because of the high iron yield.
- (ii) The second highest value for [Mg/Fe] is produced in the models with $Z = Z_\odot$. The results for $Z = 0.01 Z_\odot$ and $Z = 0.1 Z_\odot$ are in between. Hence, [Mg/Fe] is neither increasing nor decreasing with initial metallicity. The high and low WW95 metallicities *do not* bracket the expected SSP-yields as claimed by Gibson, Loewenstein, & Mushotzky (1997).
- (iii) TNH96 produce systematically higher [Mg/Fe]-ratios than WW95.

For Salpeter-IMF, the magnesium abundance in the SN II ejecta is 0.13 dex higher with TNH96-models than with WW95-models. The iron abundance, instead, is 0.08 dex lower. In total, this leads to a [Mg/Fe]-ratio, which is 0.21 dex higher for TNH96 nucleosynthesis.

We define the *time dependent* SSP-yield for element i at time t as

$$Q_{\text{SSP}}^i(t) = \frac{\int_{m_t}^{m_{\max}} Q_{im} \phi(m) dm}{\int_{m_t}^{m_{\max}} (1 - w_m) \phi(m) dm} \quad (18)$$

This equation describes the abundance of element i in the ejecta of one generation of stars of one single metallicity at the time t . With progression of time, the turnoff mass decreases and $Q_{\text{SSP}}^i(t)$ converges to the standard SSP-yield, integrated over the whole mass range. We consider enrichment due to PN, SN II, and SN Ia (see also eqn. 8). Since TNH96 models are computed only for solar metallicities, we consider WW95-yields of solar initial metallicity. The stellar lifetimes are taken from Schaller et al. (1992). For the following computations we have extrapolated TNH96 yields to $11 M_\odot$, and neglected the contribution from SN II coming from stars with mass in the range $8 - 11 M_\odot$ (see WW95). The fraction of close binary systems is $A = 0.035$. As discussed in section 5 this value is calibrated in the chemical evolution model of the solar neighbourhood. Since the value of this parameter is very small, the yields of SN II are

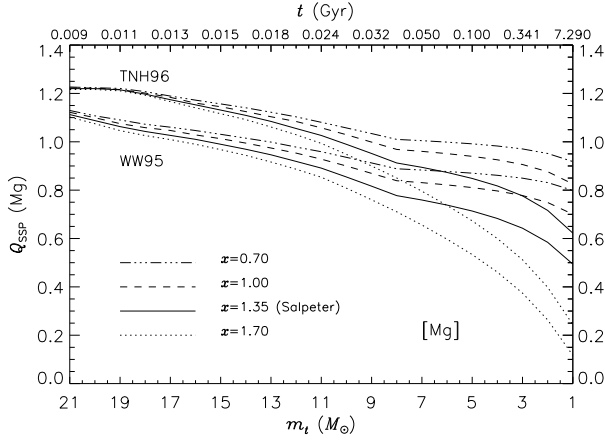


Figure 5. The figure shows the abundance of magnesium in the ejecta of one generation of stars in the range from the turnoff to the maximal mass $m = 40 M_{\odot}$. This mass range is increasing with decreasing turnoff mass m_t (lower x-axis) and with increasing time (upper x-axis). The quantity Q_{SSP} is defined in equation 18. The enrichment due to type II SNe ($11 - 40 M_{\odot}$), type Ia SNe ($3 - 16 M_{\odot}$) and planetary nebulae ($1 - 8 M_{\odot}$) is taken into account. The fraction $A = 0.035$ of binaries exploding as SN Ia is determined in the chemical evolution model for the solar neighbourhood in section 5. The calculated SSP-yield (see eqn. 18) is normalized on the solar magnesium abundance (Anders & Grevesse 1989) and plotted on a logarithmic scale. Different SSP-yields are calculated for different IMF slopes x and SN II-yields (TNH96, WW95(B,Z₀)). The total contribution of type II SNe to the SSP-yield is reached after 24 Myr when the turnoff mass is $11 M_{\odot}$. Since mainly high mass stars contribute to the enrichment of magnesium, the SSP-yield is decreasing with decreasing turnoff mass. For Salpeter-IMF, the abundance of magnesium in the ejecta of SN II is 0.13 dex higher using TNH96-yields.

only marginally affected by the choice of A . The exact number becomes important when star formation timescales of ~ 10 Gyr and enrichment due to SN Ia are considered. For the remnant masses, we adopt Renzini & Voli (1981) up to $8 M_{\odot}$, and either WW95 or TNH96 from $11 M_{\odot}$ to $40 M_{\odot}$. In the range $8 - 11 M_{\odot}$ the mass of the remnant is taken to be $1.4 M_{\odot}$.

4.1 Magnesium

Figure 5 shows the abundance of magnesium in the ejecta of one dying generation of stars as a function of turnoff mass. The abundances are normalized to solar values and plotted on a logarithmic scale. The magnesium abundance in the ejecta is significantly super-solar. The upper x-axis shows the progression of time which is not linear with the turnoff mass. The turnoff of $3 M_{\odot}$ is reached after 0.341 Gyr, but it takes more than 7 Gyr until stars of $1 M_{\odot}$ contribute to the enrichment as well. The different line styles belong to various IMF slopes. The solid line indicates the Salpeter-IMF.

One can see that the magnesium abundance in the total ejecta is decreasing with turnoff mass for $m_t < 20 M_{\odot}$. This is due to the fact that most magnesium is processed in stars more massive than $20 M_{\odot}$ (figure 3). The SN II-SSP-yield is reached at $m_t = 8 M_{\odot}$. For $m_t \leq 8 M_{\odot}$, SN Ia and PN begin to contribute. But since both events do not eject a significant

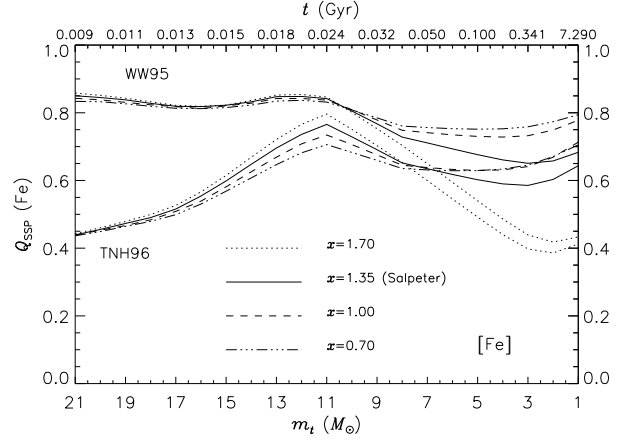


Figure 6. The figure shows the abundance of iron in the ejecta of one generation of stars in the range from the turnoff to the maximal mass $m = 40 M_{\odot}$. For a detailed description see the caption of figure 5. Since low mass stars dominate the iron yield of SN II, the maximal SN II-SSP-yield is reached at $m_t = 11 M_{\odot}$. The value decreases with the contribution of PNe and rises again when type Ia SNe enter the game. For Salpeter-IMF, the SN II-yields of WW95 lead to an iron abundance which is 0.08 dex higher.

amount of magnesium (see table 1), the abundance is still decreasing with decreasing turnoff mass and increasing time.

The most striking aspect of this diagram is that the magnesium abundance due to TNH96 nucleosynthesis is 0.13 dex higher (Salpeter IMF, model B). This is caused by the significant difference in the yields of $18 - 25 M_{\odot}$ stars as shown in figure 3. Hence, the discrepancy between WW95 and TNH96 is maximum at $m_t \approx 19 M_{\odot}$.

4.2 Iron

The iron enrichment of the SSP as a function of time is shown in figure 6. Since iron is mainly synthesized in stars of lower masses, the time dependent SSP-yield is roughly constant (WW95) or even increasing (TNH96) with increasing turnoff mass (fig. 6) until the SN II value is reached. Since stars between $8 - 11 M_{\odot}$ are assumed not to contribute to the enrichment of heavy elements, there is a peak at $11 M_{\odot}$. At late times, the contribution due to type Ia SNe comes into play, and the iron abundance in the ejecta is rising again. It is important to recognize that the iron abundance in the ejecta of SN II is higher for a steeper IMF (see dotted curve). The results from TNH96-models are more strongly dependent on the slope of the IMF than WW95, because the contribution of high mass stars to the iron production is smaller in TNH96 (see also figure 4). For the same reason, the difference between WW95 and TNH96 increases for a flatter IMF.

4.3 [Mg/Fe]

Figure 7 shows the following aspects:

- (i) In the first 10 Myr, the produced magnesium overabundance is fairly high, the difference between WW95 and TNH96 is extremely large. WW95 yields reach $[\text{Mg}/\text{Fe}] \approx 0.2$

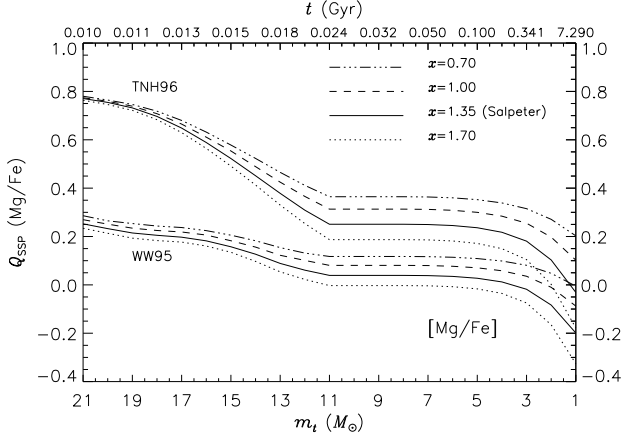


Figure 7. The figure shows the abundance ratio of magnesium over iron in the ejecta of one generation of stars in the range from the turnoff to the maximal mass $m = 40 M_{\odot}$. For a detailed description see the caption of figure 5. Since stars between 8 and $11 M_{\odot}$ do neither eject magnesium nor iron, the ratio is constant in this mass range. The further ejection of iron due to SN Ia drives the ratio down for lower turnoff masses. The ratio provided by SN II-yields of WW95 does not suffice to explain magnesium-enhanced abundance ratios, also for a rather flat IMF.

at a turnoff $m_t \approx 20 M_{\odot}$, after 10 Myr. Even considering a flat IMF with $x = 0.70$, the minimum overabundance in ellipticals of 0.2 dex (Worthey et al. 1992) is reached at $t \approx 15$ Myr when the contribution of type II SNe is not yet complete. TNH96 provide the same value of $[\text{Mg}/\text{Fe}]$ after 7.3 Gyr when SN Ia explosion are already tearing the ratio down. Obviously, this strongly affects the timescales of star formation of a system showing a $[\text{Mg}/\text{Fe}]$ overabundance.

(ii) One generation of SN II exploding stars cannot produce the magnesium overabundance in metal-poor stars in the solar neighbourhood, when considering Salpeter IMF and WW95-SN II yields. Assuming a value of $[\text{Mg}/\text{Fe}] \approx 0.3$ – which is already a lower limit – all low-metallicity stars should have been born in the first 9 million years (see also section 5).

(iii) With progression of time, the overabundance is decreasing, because more and more low mass stars ($m < 20 M_{\odot}$) with higher iron and lower magnesium yields are contributing to the enrichment. Once the turnoff mass is $8 M_{\odot}$, the final SN II-SSP value is reached.

(iv) The magnesium overabundance in the SN II output increases according to flattening of the IMF. This is because of giving more weight to magnesium producing high mass stars.

(v) The dependence of $[\text{Mg}/\text{Fe}]$ on the IMF slope is increasing with time. This is understandable, because for a larger considered mass range the role of the IMF slope becomes more important.

(vi) The TNH96-models provide a $[\text{Mg}/\text{Fe}]$ -ratio of 0.26 dex, WW95-models lead to $[\text{Mg}/\text{Fe}] = 0.05$ dex, both for Salpeter-IMF.

WW95 specify an uncertainty of a factor of 2 in the iron yield. Since this causes a shift by 0.3 dex, one could argue that simply taking half of the iron yield would solve the overabundance problem. We want to show that this is not

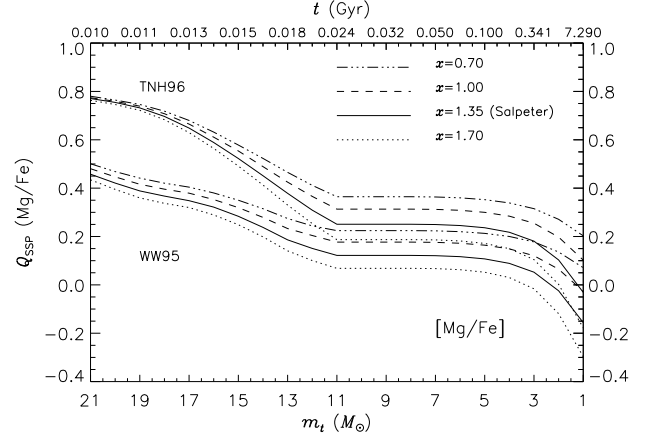


Figure 8. The diagram shows the same as figure 7. In addition, we assumed a reduced WW95-iron yield for masses above $20 M_{\odot}$ by a factor of 2, according to the uncertainty given in WW95. The iron yields of masses below $20 M_{\odot}$ are not overestimated by a factor of 2 in WW95, because they agree with the observations of SN1987A and SN1991J (see text). The SN II-SSP-yield of iron is increased by 0.08 dex, which is not enough to improve the situation significantly.

the case. Since the iron yields of stars below $20 M_{\odot}$ are very similar in the two sets of models, and since both sets reproduce the observations of SN1987A and SN1993J very well (see table 5), it is reasonable only to halve the iron yields of stars above $20 M_{\odot}$ in WW95. Re-calculating the SSP-yields with the modified Fe-yield of WW95, it turns out that the total $[\text{Fe}]$ is only shifted by 0.08 dex to lower values. Figure 8 shows the $[\text{Mg}/\text{Fe}]$ -ratio as a function of the turnoff mass in this experiment. The plot shows, that it remains difficult to reproduce the observed magnesium overabundances with WW95 nucleosynthesis.

It is important to mention that also TNH96 magnesium yields may not suffice to explain observed $[\text{Mg}/\text{Fe}]$ overabundances in elliptical galaxies. There are several indications that $[\text{Mg}/\text{Fe}]$ in nuclei of ellipticals does even exceed 0.4 dex (Weiss et al. 1995; Mehlert et al. 1997). As demonstrated in figure 7, this value can not be theoretically produced by one SN II-exploding generation of stars. Hence, claiming $[\text{Mg}/\text{Fe}] \gtrsim 0.4$ dex, the star forming phase in giant ellipticals must be of the order 10^7 yr, even for TNH96-yields and a flat IMF ($x = 0.7$). A detailed exploration of star formation timescales, IMF-slopes and stellar yields in elliptical galaxies will be the subject of a forthcoming paper.

Finally, one should not forget, that the number of input parameters in the calculations is very small. The above conclusions do not depend on galaxy formation scenarios, on star formation histories, on infall models, or on binary fractions. The only considered parameters are the IMF slope and stellar yields.

4.4 $[\text{O}/\text{Fe}]$

Figure 9 shows the time dependent SSP yield as a function of turnoff mass for the abundance ratio $[\text{O}/\text{Fe}]$. Since both, oxygen and magnesium, are produced mainly in type

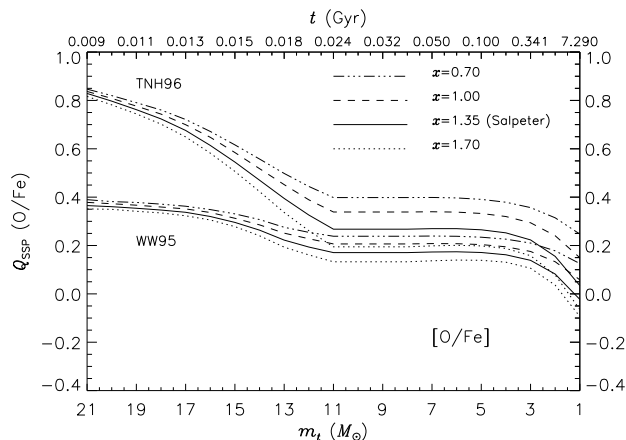


Figure 9. The figure shows the abundance ratio of oxygen over iron in the ejecta of one generation of stars in the range from the turnoff to the maximal mass $m = 40 M_{\odot}$. For a detailed description see the caption of figure 5. Oxygen and magnesium overabundances in the ejecta of SN II are the same for TNH96-yields. With WW95, instead, the SSP-value of $[O/Fe]$ is ~ 0.12 dex higher than $[Mg/Fe]$. Since both are α -elements and should therefore be enhanced by approximately the same amount, this is a further indication that WW95 underestimate the magnesium yield of SN II.

II supernovae, one would expect similar values for the overabundance.

For TNH96, this is exactly the case. The contribution of low mass stars ($1 M_{\odot} \leq M \leq 8 M_{\odot}$) to the enrichment of oxygen manifests itself in an elongation of the SN II plateau down to $5.5 M_{\odot}$. Although SN Ia produces 6 times more oxygen than magnesium, the SN Ia tears the curve down by approximately the same amount because of the dominant role of iron in the ejecta. The WW95- $[O/Fe]$ -ratio, instead, is 0.12 dex higher than $[Mg/Fe]$.

The discrepancy between WW95 and TNH96 $[O/Fe]$ -ratios now originates mainly from the discrepancy in the iron yields, while oxygen yields differ by 0.02 dex. This leads again to the conclusion, that WW95 may underestimate the magnesium yield.

4.5 On the upper mass cutoff

In this paragraph, we will investigate the influence of a variation of the upper mass cutoff on the calculated SSP-yields. For this purpose, we include the results of TNH96 for the $70 M_{\odot}$ -star. In order to compare the different nucleosynthesis prescriptions, we have to extrapolate the WW95-yields to higher masses, hence the result has to be interpreted with cautions. In the WW95-models most heavy elements re-implode for the massive stars, so that the contribution of these stars to the enrichment is negligible. Indeed, the plots in figures 2 and 3 show this trend for the elements oxygen and magnesium, respectively (also model B). TNH96 do not consider fall back, thus their O-Mg-yields increase with mass up to $m = 70 M_{\odot}$.

Table 6 gives the variation of the abundances of various elements in the SN II ejecta of one SSP, if $m_{\max} = 70 M_{\odot}$ with respect to the $m_{\max} = 40 M_{\odot}$ case. These reflect both the metal production and the total ejected mass in the range

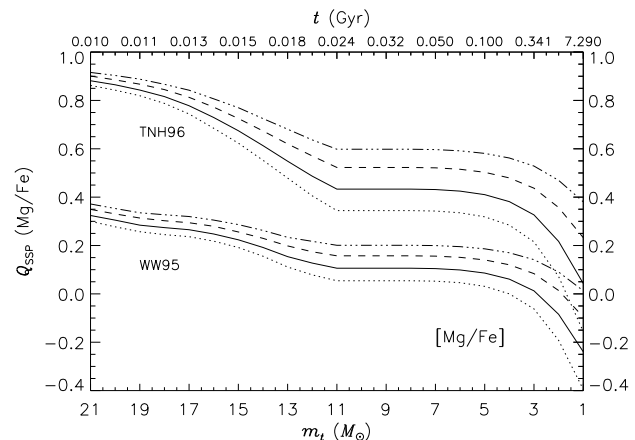


Figure 10. The figure shows the abundance ratios of magnesium over iron in the ejecta of one generation of stars in the range from the turnoff to the maximal mass $m = 70 M_{\odot}$. For a detailed description see the caption of figure 5. The consideration of a higher maximum mass leads to larger $[Mg/Fe]$ -ratios for TNH96-models. The results for WW95 basically do not change. However, the WW95-yields are extrapolated to $70 M_{\odot}$ and are therefore uncertain.

40 – 70 M_{\odot} . The following striking aspects should be mentioned:

- (i) The iron abundance in the ejecta decreases for all models. This effect is strongest for flatter IMF and WW95-models.
- (ii) The oxygen abundance, instead, increases for all models. Again the effect is strongest for a flatter IMF, but more important in TNH96.
- (iii) The behaviour of the magnesium abundance is more complex. For TNH96 the increase of magnesium becomes more significant with a flatter IMF, whereas for WW95 the pattern is inverse.

In total, the $[Mg/Fe]$ -ratio in the SSP-ejecta increases significantly only for TNH96-models. In the WW95-models, the effect of fall back prevents a significant change. This is confirmed in figure 10 in which we show the abundance ratios as a function of turnoff mass and time with $m_{\max} = 70 M_{\odot}$ considered. The diagram shows that assuming a larger value for m_{\max} the problem of the magnesium overabundance is relaxed, *if the high Mg-yield calculated by TNH96 in high mass stars is correct*. This seems to us still controversial. It is of great importance in the future to improve the knowledge on the stellar yields of these stars, too.

Furthermore, it is worth noting that the abundance ratio of magnesium to oxygen decreases with the inclusion of stars more massive than $40 M_{\odot}$. This is important because it becomes even more difficult to reproduce the solar Mg/O ratio. We give a detailed exploration on this aspect in paragraph 5.3 of the next section.

5 THE SOLAR NEIGHBOURHOOD

5.1 The model parameters

The chemical evolution of our galaxy is treated in the literature several times (e.g. Matteucci & Greggio 1986; Timmes

Table 6. The numbers give the shift of the abundances in the ejecta of one SSP when the maximum mass is increased from 40 to 70 M_{\odot} . The yields of WW95 are extrapolated to masses above 40 M_{\odot} .

| | $x = 1.7$ | | | $x = 1.35$ | | | $x = 1.0$ | | | $x = 0.7$ | | |
|-------|--------------------|---------------------|---------------------|--------------------|---------------------|---------------------|--------------------|---------------------|---------------------|--------------------|---------------------|---------------------|
| | $\Delta[\text{O}]$ | $\Delta[\text{Mg}]$ | $\Delta[\text{Fe}]$ | $\Delta[\text{O}]$ | $\Delta[\text{Mg}]$ | $\Delta[\text{Fe}]$ | $\Delta[\text{O}]$ | $\Delta[\text{Mg}]$ | $\Delta[\text{Fe}]$ | $\Delta[\text{O}]$ | $\Delta[\text{Mg}]$ | $\Delta[\text{Fe}]$ |
| TNH96 | 0.20 | 0.14 | -0.01 | 0.23 | 0.17 | -0.01 | 0.26 | 0.19 | -0.01 | 0.28 | 0.22 | -0.02 |
| WW95 | 0.09 | 0.02 | -0.03 | 0.11 | 0.02 | -0.05 | 0.12 | 0.01 | -0.06 | 0.13 | 0.00 | -0.09 |

et al. 1995; Pagel & Tautvaisiene 1995; Tsujimoto et al. 1995, Yoshii et al. 1996). The model predictions fit the data quite well, the main observational features can be reproduced. In the classical numerical models, the chemical evolution of the ISM in the solar neighbourhood is described in a one-zone model of homogeneous and instantaneously mixing gas. The latter assumption is called the instantaneous *mixing* approximation. The instantaneous *recycling* approximation, which neglects the stellar lifetimes is relaxed in these models as well as in our calculations. In principle, the accretion of gaseous matter over a timescale of ~ 4 Gyr enables us to avoid the formation of extremely metal-poor stars with $[\text{Fe}/\text{H}] < -3$, known as the G-dwarf problem (Larson 1972; Tosi 1988; Matteucci & François 1989). The formation of the disk in the solar vicinity due to accretion $f(t)$ is described in the following equation (Timmes et al. 1995):

$$f(t) = [M_{\text{tot}}(t_{\text{now}}) - M_{\text{tot}}(t_0)] \times \frac{\exp(-t/\tau_{\text{disk}})}{\tau_{\text{disk}}[1 - \exp(-t_{\text{now}}/\tau_{\text{disk}})]}, \quad (19)$$

with $M_{\text{tot}}(t_{\text{now}} = 15 \text{ Gyr})$ and $M_{\text{tot}}(t_0 = 0 \text{ Gyr})$ as the surface densities ($M_{\odot}\text{pc}^{-2}$) of the total mass (stars+gas) today and at the beginning of the disk formation, respectively. The accretion timescale for the formation of the disk is controlled by the parameter τ_{disk} .

The SFR is assumed to depend on the gas density of the ISM (Schmidt 1959; Schmidt 1963) with ν (Gyr^{-1}) as the efficiency of star formation (free parameter).

$$\psi(t) = \nu M_{\text{tot}} \left[\frac{M_g(t)}{M_{\text{tot}}(t)} \right]^k \quad (20)$$

In the literature, the adopted value for the exponent k varies between $k = 1$ and $k = 2$ (e.g. Matteucci & François 1989). In the following section, we will show the influence of this parameter on the observational features. The Schmidt-law together with the infall of gas over a relatively long timescale guarantee a roughly continuous star formation during the evolution of the solar neighbourhood.

Furthermore, the enrichment of the ISM due to PN, SN II and SN Ia is considered, using supernova rates as described in section 2. The parameter A in equations 10 and 11 is a free parameter. It is calibrated on the current supernova rates in our Galaxy. As shown in the previous sections, especially the yields of type II SNe are affected by many uncertainties. Hence, we treat the SN II-yields as a parameter in the sense that we consider the different SN II nucleosynthesis prescriptions presented in section 3 (WW95 and TNH96). TNH96-yields consist of the given yield from the evolution of the helium core plus the initial abundance of the element in the envelope (see also section 3). In the simulations of the chemical evolution, the initial element abundances of

the envelopes correspond to the element abundances in the ISM when the star forms. In these terms, the TNH96-yields become metallicity dependent, although the evolution of the helium core is only calculated for solar element abundances.

The basic equations of chemical evolution are explained in section 2. Since SN Ia explode delayed with respect to SN II (Greggio & Renzini 1983), the element abundances in metal-poor stars are determined mainly by SN II. Hence, the adopted standard model for the chemical evolution in the solar neighbourhood can easily explain the enhancement of α -elements in metal-poor stars, assuming the $[\text{Mg}/\text{Fe}]$ -ratios given by SN II nucleosynthesis are high enough.

5.2 Observational constraints

There are several observational features in the solar neighbourhood basically constraining different parameters. In the subsections below, we will discuss in detail the influence of the parameters on the abundance distribution function (ADF), the age-metallicity relation (AMR), the current supernova rates, and the element abundances in the sun. The parameters have to be adjusted to provide the best possible *simultaneous* fit to the existing observational data. In table 7 we summarize how the various parameters can be constrained by the different observational features. The right column of the table gives the final adopted values. The calculations are performed using the stellar yields of TNH96. Additional computations for WW95-yields under the same conditions are made in order to work out the influence of stellar nucleosynthesis. The galactic age is assumed to be $t_{\text{now}} = 15 \text{ Gyr}$ (Timmes et al. 1995), the age of the sun is 4.5 Gyr. The value of the surface density in the solar neighbourhood is assumed to be $77 M_{\odot}\text{pc}^{-2}$ (Kuijken & Gilmore 1989a; Kuijken & Gilmore 1989b; Kuijken & Gilmore 1989c; Statler 1989; Gould 1990; Kuijken & Gilmore 1991). Stellar lifetimes are taken from Schaller et al. (1992).

5.2.1 Abundance Distribution Function

The differential ADF gives the number of stars that are born per unit metallicity as a function of metallicity. Pagel & Patchett (1975) derived this relation for the solar vicinity ($\sim 25 \text{ pc}$) with a sample of 132 G-dwarfs. The most important feature of the ADF is the paucity of extremely metal-poor stars. Assuming a closed box for the chemical evolution, the so called *Simple Model* predicts too many metal-poor stars (van den Bergh 1962; Schmidt 1963; Tinsley 1980). This deviation is known as the G-dwarf problem. The considerations of pre-enrichment (Truran & Cameron 1971) or infall of material (Larson 1972) help to avoid the formation of low-metallicity stars. The latter possibility is used in the adopted model for the solar neighbourhood, assuming the

Table 7. Input parameters in the calculations for the chemical evolution of the solar neighbourhood. The parameters are chosen to match simultaneously the observational constraints: ADF, AMR, supernova rates, solar element abundances, current infall rate, and current fraction of gaseous mass. The second column shows the main observational constraints on the respective parameter. The third column gives the final adopted values.

| Parameter | Observational constraint | Adopted value |
|--|--|------------------------|
| Stellar yields | Element abundances of the sun | TNH96 |
| IMF slope x | Solar abundance ratios | 1.36 |
| Close binary fraction A | Relative frequency of type II and Ia SNe | 0.035 |
| | AMR | |
| Star formation efficiency ν | current fraction of gaseous mass | 1.3 Gyr^{-1} |
| Schmidt exponent k | ADF | 2 |
| Accretion timescale τ_{disk} | current infall rate | 4 Gyr |
| | ADF | |

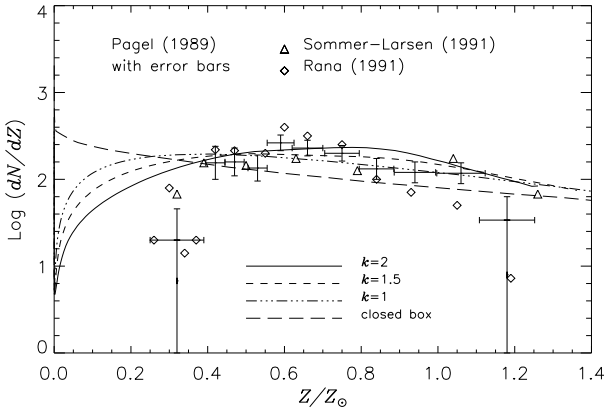


Figure 11. The abundance distribution function (ADF) giving the number of stars that are born per unit metallicity $\log(dN/dZ)$ as a function of metallicity. The observational data points with error bars refer to the reanalysis of the Pagel & Patchett data (1975) by Pagel (1989), taking the metallicity-excess calibration of Cameron (1985) into account. Additional re-interpretations of the data set by Rana (1991) and Sommer-Larsen (1991) respective with correction for the increase of the velocity dispersion with time and the correction for the vertical height distribution of dwarfs. The long-dashed line shows the calculated ADF for a closed box model without infall. While this model definitely fails to match the observations, the models with the inclusion of infall can reproduce at least the general shape of the observed ADF. The best fit refers to the exponent $k = 2$ of the Schmidt-law for fixed accretion timescale $\tau_{\text{disk}} = 4 \text{ Gyr}$. The parameters ν and k are chosen such that the same amount of gas is converted to stellar mass in all models.

disk to form due to accretion of primordial gas (see equation 19).

The shape of the resulting theoretical ADF depends basically on dynamical parameters like the accretion timescale τ_{disk} and the Schmidt-law exponent k (Matteucci & François 1989). Figure 11 shows the results for different choices of the parameter k . To guarantee that in all computations the same total number of stars is formed, the star formation efficiency ν (see equation 20) is reduced for smaller k . The diagram demonstrates the following:

- (i) The inclusion of infall solves the G-dwarf problem in

the sense that the extremely high amount of metal-poor stars as predicted by the closed box model (long-dashed line) is significantly decreased. The general shape of the ADF, the peak at intermediate metallicities, is reproduced by the model.

- (ii) The smaller the exponent k is, the more stars of high and low metallicity are formed. Since the ADF predicted by the model is already too flat, $k = 2$ may be the best choice.

A better fit to the ADF-data requires an improvement of the adopted model. Since there are both, too many metal-poor and metal-rich stars, a different description of the infall-term may be necessary. In addition, the consideration of pre-enrichment of the infalling gas further reduces the number of low metallicity stars. Since the aim of this work is to inspect the influence of different stellar yields on the chemical evolution in the solar vicinity in the framework of the standard infall-model model, we simply use the ADF to constrain the model parameters without improving the model to obtain better fits.

Figure 12 shows the ADF for different accretion timescales. For $\tau_{\text{disk}} = 3 \text{ Gyr}$ and $\tau_{\text{disk}} = 5 \text{ Gyr}$ the number of metal-poor and metal-rich stars is overestimated, respectively. Thus, we use $\tau_{\text{disk}} = 4 \text{ Gyr}$ in our simulations.

5.2.2 Age Metallicity Relation

The age metallicity relation (AMR) shows the ratio $[\text{Fe}/\text{H}]$ indicating the metallicity as a function of the ages of the stars (Twarog 1980). Since different element abundances of the ISM at different times are locked in stars of different ages, this corresponds to the evolution of $[\text{Fe}/\text{H}]$ in the ISM as a function of time. In the first 2 Gyr of the evolution when the SFR is at its maximum, $[\text{Fe}/\text{H}]$ rises very steeply to a value of $\sim -0.5 \text{ dex}$. The increase flattens out significantly and emerges to solar metallicity at $t \approx 10 \text{ Gyr}$. Figure 13 shows, that this behaviour is well reproduced by the simulations. Star formation (dotted line) is occurring over the whole range of 15 Gyr with a peak of $11 M_{\odot} \text{ pc}^{-2} \text{ Gyr}^{-1}$ at $t = 1.9 \text{ Gyr}$. Fitting an exponential law like

$$\psi(t) \sim \exp^{-t/\tau}$$

to the range 5 – 15 Gyr where the SFR is decreasing leads to $\tau \approx 8 \text{ Gyr}$.

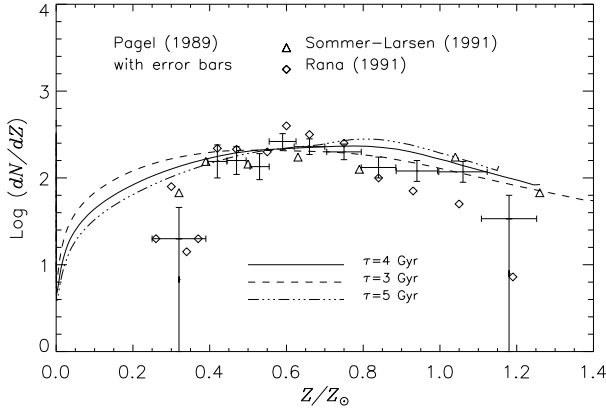


Figure 12. The abundance distribution function (ADF) giving the number of stars that are born per unit metallicity $\log(dN/dZ)$ as a function of metallicity. For a short description of the data points see figure 11. In this plot, the accretion timescale is varied. Since a longer accretion timescale supports the formation of metal-rich stars, the best fit to the data is obtained for $\tau_{\text{disk}} = 4$ Gyr. The Schmidt exponent is $k = 2$ as worked out above.

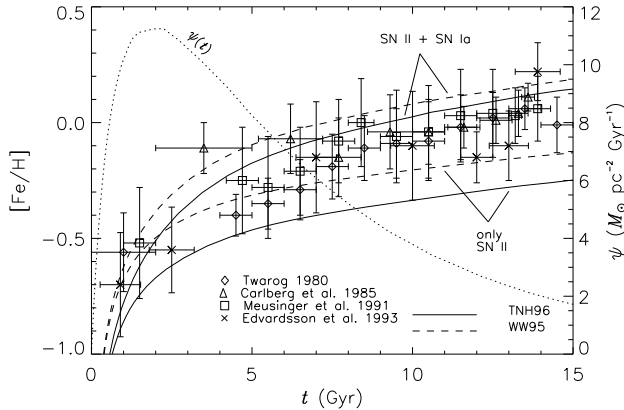


Figure 13. The age-metallicity relation (AMR) for the solar neighbourhood. The symbols indicate the observational data, where the error bars denote the spread of many stars in the data. Twarog (1980) determined age and metallicity for two samples of 1007 and 2742 local disk stars, respectively. Carlberg et al. (1985) and Meusinger, Reimann, & Stecklum (1991) reanalysed these data using new isochrones from Vandenberg (1985). Edvardsson et al. (1993) did not re-examine the Twarog-data but derived abundances for 189 F and G disk dwarfs in the solar vicinity. The plot shows that for both SN II nucleosynthesis prescriptions, the enrichment due to type Ia SNe is necessary to reproduce the AMR in the solar neighbourhood. A comparison between the solid and the dashed lines (TNH96 and WW95 (model B) SN II-yields, respectively) confirms the result from section 4 that WW95 produce ~ 0.08 dex more iron. The dotted curve shows the SFR ($M_{\odot} \text{pc}^{-2} \text{Gyr}^{-1}$) as a function of time. The value for today ($t = 15$ Gyr) is in agreement with observations (Güsten & Mezger 1983).

The iron abundance at large t is significantly determined by the contribution of type Ia SNe. The simulations excluding enrichment by SN Ia clearly underestimate the production of iron.^{||} Furthermore, the fraction of iron contributed by the different types of SNe depends on the adopted stellar yields. WW95 models (dashed lines) produce ~ 0.08 dex more iron than TNH96 (see section 4). Using TNH96 yields, 60 per cent of the produced iron comes from type Ia SNe, according to WW95 models this amount decreases to 50 per cent. Because of the higher iron yield, WW95 models fit the AMR-relation worse, but are still within the error bars.

The total amount of iron in the ISM highly depends on the fraction A of close binary systems. The AMR could be slightly better fitted for a reduced iron production, thus for a lower parameter A . However, this parameter is additionally constrained by the relative frequency of the different types of supernovae.

5.2.3 Supernova rates

Unfortunately, the current rates of both types of SNe (Ia and II) in spiral galaxies and in the solar neighbourhood are still uncertain (van den Bergh & Tammann 1991). Since there is no consensus, the range allowed by observations is fairly large. The theoretical relative frequency of SN II and SN Ia is mainly determined by the parameter A . In their review paper, van den Bergh and Tammann (1991) claim $N_{\text{SNII}}/N_{\text{SNIa}} \approx 2.7$ for Sab-Sb galaxies and $N_{\text{SNII}}/N_{\text{SNIa}} \approx 8$ for Sc-Scd galaxies. Since our Galaxy is assumed to have a Hubble type between Sb and Sc (van den Bergh & Tammann 1991), a relative frequency of $N_{\text{SNII}}/N_{\text{SNIa}} \approx 5$ seems to be a reasonable estimate. This value is in agreement with our calculations.

Figure 14 shows the rates of type II and type Ia SNe as a function of time. While the relative frequency of SN II and SN Ia basically constrains the parameter A , the absolute number of type II SNe occurring today depends on the parameters ν , k , and τ_{disk} , whose values are already chosen to fit the ADF. Assuming that SNe II occur in stars above $8 M_{\odot}$, Tammann (1982; 1991) estimates a surface density of $N_{\text{SNII}} \approx 0.02 \text{ pc}^{-2} \text{Gyr}^{-1}$ in the solar neighbourhood from historical data. However, because of the small size of the sample, this value is quite uncertain. Indeed, van den Bergh (1991) claims that the historical data may overestimate the absolute number of SN II significantly. Thus, the calculated value of $N_{\text{SNII}} \approx 0.01 \text{ pc}^{-2} \text{Gyr}^{-1}$ is still acceptable.

5.2.4 Solar element abundances

The model assumes that disk formation started 15 Gyr ago. Since the sun is ~ 4.5 Gyr old, the element abundances in the ISM predicted by the model have to be solar at $t \approx 10.5$ Gyr.

In section 2, we showed how to constrain the SFR (parameters ν and k), the IMF slope (x) and the stellar yield from observational data of the accretion rate, the current gas

^{||} This statement is basically independent of m_{min} , since the abundance *ratio* of iron to oxygen is underestimated without SN Ia.

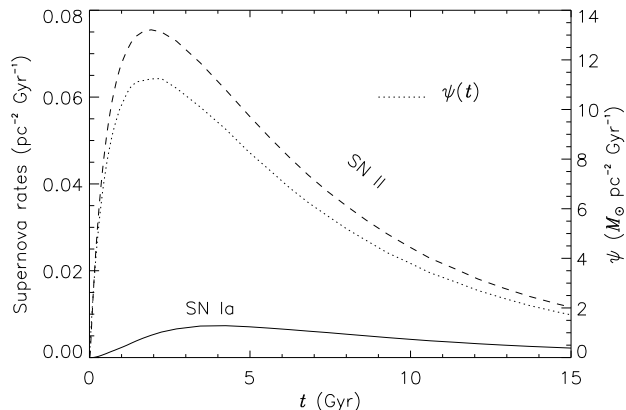


Figure 14. The plot shows the rates of both types of supernovae and the SFR as a function of time. The enrichment due to SN Ia is delayed with respect to SN II. The dotted curve demonstrates that the rate of type II SNe – occurring in high mass and short-living stars – directly depends on the SFR. The calculated number ($\text{pc}^{-2}\text{Gyr}^{-1}$) of SN II occurring today is in rough agreement with observational estimates (see text). The relative frequency of SN II to SN Ia is highly dependent on the parameter A and is in agreement with observations (van den Bergh & Tammann 1991). The fraction A of close binaries has to be chosen to fit the supernova rates and the AMR (figure 13) simultaneously.

fraction and the element abundances. The timescale for disk formation τ_{disk} is constrained by the accretion rate which is observed today (see caption of table 8)**. Having fixed $f(t)$ and m_{min} , the current fraction of gaseous mass constrains the mean SFR ($\rightarrow \nu, k$), depending on the IMF slope. We showed that, considering an element whose yield is relatively certain, the calculated solar abundance of this element depends on $\bar{\psi}$ and x . Thus, τ_{disk} , ν , k , and x are fixed.

Figure 2 shows that WW95 and TNH96 differ only slightly in the calculated oxygen yield. Furthermore, oxygen is mainly produced in massive stars of small stellar lifetimes τ_m , thus the neglect of τ_m in the arguments in section 2 is valid. Hence, we assume this yield to be the most certain and use oxygen to pin down the IMF slope. Having done this, we can analyse if the stellar yields of various elements are in agreement with observations. Table 8 shows the comparison between the calculated quantities and their observational constraints. The element abundances of ^1H , ^{16}O and Z are best reproduced (due to the above strategy): WW95 and TNH96 differ only marginally, the deviations from observational data are between 1 and 4 per cent. However, in the case of magnesium, the situation is different: the calculated ^{24}Mg -abundance deviates from observational data by 7 per cent (TNH96) and 29 per cent (WW95). Reproducing the solar oxygen abundance, the calculated magnesium abundance is too low, especially with WW95 nucleosynthesis. Hence, the predicted ratio between the two element abundances is not in agreement with observations. Since SN II is the main contributor to the Mg-enrichment, we can conclude that the

** The today's accretion rate of $0.2 - 1.0 M_{\odot}\text{pc}^{-2}\text{Gyr}^{-1}$ estimated from observations of high velocity H I clouds (see Timmes et al. 1995 and references therein) allows $\tau_{\text{disk}} \approx 3 - 5.5$ Gyr. The more specific value of 4 Gyr is constrained by the ADF.

Table 8. Numerical results of the chemical evolution in the solar neighbourhood compared with observational constraints. The adopted input parameters are given in table 7. The current fraction of gas $M_g/M_{\text{tot}}(t_{\text{now}})$ is taken from Rana & Basu (1992), the current accretion rate ($M_{\odot}\text{pc}^{-2}\text{Gyr}^{-1}$) comes from observations of high velocity H I clouds (see Timmes et al. 1995 and references therein). Solar element abundances (by mass) are adopted from Anders & Grevesse (1989), meteoritic values.

| | TNH96 | WW95 | Observation |
|--------------------------------------|----------|----------|-----------------|
| $M_g/M_{\text{tot}}(t_{\text{now}})$ | 0.13 | 0.13 | 0.10 ± 0.03 |
| $f(t_{\text{now}})$ | 0.46 | 0.46 | $0.2 - 1.0$ |
| Solar Z | 1.96(−2) | 1.86(−2) | 1.88(−2) |
| Solar ^1H | 6.96(−1) | 6.89(−1) | 7.06(−1) |
| Solar ^{16}O | 9.92(−3) | 9.36(−3) | 9.59(−3) |
| Solar ^{24}Mg | 4.80(−4) | 3.68(−4) | 5.15(−4) |
| Solar ^{56}Fe | 1.26(−3) | 1.41(−3) | 1.17(−3) |

magnesium yield of type II SNe is clearly underestimated by WW95.

Although ^{56}Fe also deviates from the observational value, one cannot directly draw conclusions on the iron yield of type II supernovae, because of the large contribution due to type Ia SNe.

5.2.5 $[\text{Mg}/\text{Fe}]$

We now turn to consider the element abundances observed in stars of various metallicities in the solar neighbourhood, being the last important observational constraint on theoretical models. Gratton & Snenen (1988) and Magain (1989) determined $[\text{Mg}/\text{Fe}]$ in metal-poor halo stars, Edvardsson et al. (1993) determined $[\text{Mg}/\text{Fe}]$ in disk stars with $[\text{Fe}/\text{H}] \geq -1$. These data together with the theoretical predictions from the model using the parameters of table 7 are plotted in figure 15.

The scatter of the data for $[\text{Fe}/\text{H}] < -1$ is extremely large. A reasonable average in the range $-3 \leq [\text{Fe}/\text{H}] \leq -1$ seems to be $0.3 \leq [\text{Mg}/\text{Fe}] \leq 0.4$ dex. While TNH96- $[\text{Mg}/\text{Fe}]$ -yields are high enough to fit this value, WW95 fail to reproduce such large values. The same preliminary conclusion was already made in section 4.

Timmes et al. (1995) also realized, that the produced $[\text{Mg}/\text{Fe}]$ -ratio in WW95 is too low to explain the data, and suggested a reduction of the SN II iron yield by a factor of 2. On the other hand, as discussed in section 4, the iron yields of stellar masses smaller than $20 M_{\odot}$ are in good agreement with the observational data from SN1987A and SN1991J. Thus, it is reasonable to halve the iron yield of stellar masses greater than $20 M_{\odot}$. We showed that this results in a shift of 0.08 dex to higher $[\text{Mg}/\text{Fe}]$ -values, which is not enough to explain a $[\text{Mg}/\text{Fe}]$ overabundance of 0.3 – 0.4 dex.

Since a flatter IMF would result in an overestimation of the solar metallicity and oxygen abundance, the observed trend can only be produced with an increased Mg-yield. Since it is the Mg/O ratio which is underestimated, a variation of m_{min} is not suitable to solve the problem, either.

Timmes et al. (1995) claim that a small contribution of type Ia SNe or intermediate- and low-mass stars to the magnesium enrichment could solve the problem without in-

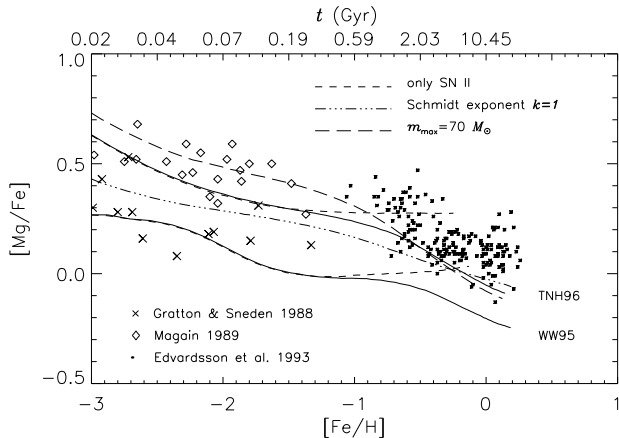


Figure 15. The abundance ratio $[Mg/Fe]$ as a function of $[Fe/H]$ and time (upper x-axis). Magain (1989) derived element abundances in 20 metal-poor halo stars leading to a mean $[Mg/Fe]$ of 0.48 dex. Gratton & Sneden (1988) measured the abundances of 12 metal-poor field giants and derived a mean $[Mg/Fe] \approx 0.27$ dex. The two solid lines show the results of the simulations for SN II-yields of TNH96 and WW95 (model B), respectively, taking enrichment due to both types of SNe into account. The dashed curve corresponds to calculations only considering SN II. The abundance ratio reaches the SN II-SSP-value, once a complete SN II-generation of stars enriches the ISM ($m_t \leq 11 M_\odot$). The value of the ‘plateau’ is approximately the SSP-value of SN II as given in table B5. At higher metallicities, the iron-dominated ejecta of SN Ia drive the ratio down. The plot shows that the $[Mg/Fe]$ -ratio in the ejecta of WW95-SNe is too low to explain the observational data. The dashed-dotted and the long-dashed lines show the results for $k = 1$ and $m_{\max} = 70 M_\odot$, respectively (both TNH96 yields).

creasing the SN II-yields. But both alternatives seem to be unlikely for the following reasons:

- (i) Low-mass stars ($1-8 M_\odot$) form CO-WD and therefore do not burn carbon to magnesium (Renzini & Voli 1981).
- (ii) Intermediate-mass stars ($8-11 M_\odot$) may even produce a lower $[Mg/Fe]$ -ratio than high-mass stars, because the ratio decreases with decreasing mass (see figure 4). If this trend can be approximately extrapolated to lower masses, those stars do not increase the value of $[Mg/Fe]$ in the ISM.
- (iii) SN Ia may be a candidate for a higher magnesium production. On the other hand, the $[Mg/Fe]$ -ratio is underestimated in a regime at low metallicities, where type II SN products dominate and type Ia SNe do not play any role.

However, uncertainties in convection theory and stellar evolution are high enough to cause different Mg-yields of SN II, which is convincingly demonstrated in the discrepancy between WW95 and TNH96.

The observational data points in figure 15 show two different slopes at different metallicity ranges. The progression of $[Mg/Fe]$ is very flat in the low $[Fe/H]$ -region and only slightly decreasing with increasing metallicity. This belongs to the regime in the first 70 Myr (see scale at the upper x-axis), where type II supernovae are dominating the enrichment of the ISM. For $[Fe/H] \gtrsim -1$, type Ia supernovae enter the game and drive down the $[Mg/Fe]$ -ratio because of their iron dominated ejecta. The decrease of $[Mg/Fe]$ with increas-

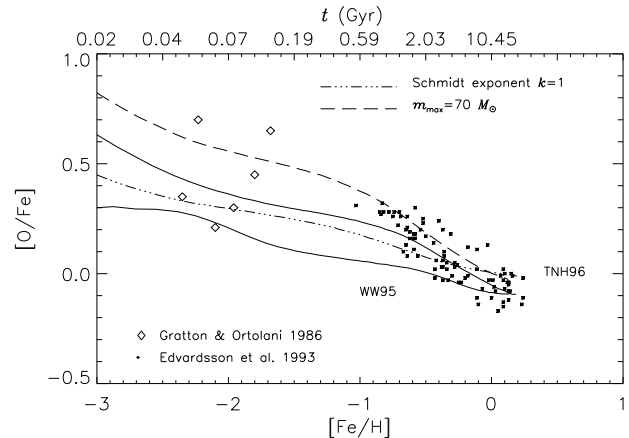


Figure 16. The abundance ratio $[O/Fe]$ as a function of $[Fe/H]$ and time (upper x-axis). The two solid lines show the results of the simulations for SN II-yields of TNH96 (upper line) and WW95, respectively. The diagram shows that the $[O/Fe]$ -ratio in the solar neighbourhood is well fitted by the model. The dashed-dotted and the long-dashed lines show the results for $k = 1$ and $m_{\max} = 70 M_\odot$, respectively (both TNH96 yields).

ing $[Fe/H]$ becomes notably steeper. Although the theoretical curves reflect this behaviour roughly, using TNH96 yields the slope at low metallicities is still too steep, especially for $-3 \leq [Fe/H] \leq -2$.

This decrease becomes flatter for the smaller Schmidt exponent $k = 1$ as indicated by the dashed-dotted line. However, while the choice of $k = 1$ may improve the agreement with the data in the $[Mg/Fe]$ - $[Fe/H]$ -diagram, the ADF is worse reproduced (see figure 11). The offset to the data of ~ 0.1 dex seems to have its origin in a too low magnesium yield. Since the model parameters are chosen to reproduce the solar oxygen abundance, it is interesting to consider the $[O/Fe]$ ratio as a function of $[Fe/H]$, too.

5.2.6 $[O/Fe]$

Again we compare the theoretical results with observations by Edvardsson et al. (1993) at high metallicities and Gratton & Ortolani (1986) in the low metallicity regime (figure 16). These data points are very few and show a large scatter. Thus we concentrate on the discussion of the Edvardsson et al. data. These are well fitted by the model using TNH96 nucleosynthesis, hence the oxygen abundance in the solar neighbourhood is reproduced as well. The calculation with a lower Schmidt-exponent k (TNH96 yields, dashed-dotted line) clearly fails to match the observed $[O/Fe]$. Although WW95-models suffice to produce a solar $[O/Fe]$ ratio, they give a bad fit to the data for $[Fe/H] < 0$.

5.3 On the upper mass cutoff

As already mentioned, we additionally performed calculations with $m_{\max} = 70 M_\odot$ and TNH96 nucleosynthesis. The fitting parameters had to be re-adjusted, the new values and the results for the calculated solar abundances are given in table 9. Again, the parameters were chosen to match the observational constraints simultaneously.

Table 9. Same as table 8, considering different upper mass cut-offs for TNH96 nucleosynthesis. In order to maintain the agreement with the discussed observational constraints, the following input parameters had to be re-adjusted: $x = 1.5$, $A = 0.06$, $\nu = 1.1 \text{ Gyr}^{-1}$.

| | 40 M_{\odot} | 70 M_{\odot} | Observation |
|--------------------------------------|----------------|----------------|-----------------|
| $M_g/M_{\text{tot}}(t_{\text{now}})$ | 0.13 | 0.13 | 0.10 ± 0.03 |
| $f(t_{\text{now}})$ | 0.46 | 0.46 | $0.2 - 1.0$ |
| Solar Z | 1.96(−2) | 1.81(−2) | 1.88(−2) |
| Solar ^1H | 6.96(−1) | 7.17(−1) | 7.06(−1) |
| Solar ^{16}O | 9.92(−3) | 9.93(−3) | 9.59(−3) |
| Solar ^{24}Mg | 4.80(−4) | 4.43(−4) | 5.15(−4) |
| Solar ^{56}Fe | 1.26(−3) | 1.21(−3) | 1.17(−3) |

The solar Mg abundance is even worse reproduced, since the ratio of magnesium to oxygen decreases with the inclusion of 70 M_{\odot} -stars (see also table 6).

A further remarkable effect is the stronger influence of type Ia SNe on the enrichment of iron (parameter A), because iron is the only element (of the considered ones) that is not additionally ejected by extremely high mass stars. The ratio $N_{\text{SN II}}/N_{\text{SN Ia}} \approx 3$ is still within the range allowed by observation, it may be even a better fit to the historical data (see discussion above).

The effect on the $[\text{Mg}/\text{Fe}]$ - $[\text{Fe}/\text{H}]$ -diagram is shown by the long-dashed curve in figure 15. The ratio $[\text{Mg}/\text{Fe}]$ is higher by ~ 0.1 dex in the low metallicity regime, whereas it is still too small at higher metallicities ($-0.7 \leq [\text{Fe}/\text{H}] \leq 0.3$). The long-dashed line in figure 16 shows that the oxygen abundance in the solar neighbourhood can still be reproduced.

The other observational constraints are also matched. The differential ADF changes as if there was a kind of pre-enrichment: it increases more rapidly at the lower Z . However already at $Z/Z_{\odot} = 0.05$ it presents too many objects, with respect to the observations.

5.4 Delayed mixing

The upper x-axis in figure 15 shows that the steep decrease of the TNH96-curve at low metallicities comes from the short timescales in this regime. On the other hand, this is a consequence from the IMA, assuming that the stellar ejecta mix immediately with the ISM. Although there is no doubt that this assumption is not realistic (Schmidt 1963; Tinsley 1975), most chemical evolution calculations hold this approximation. The validity of the IMA depends on the timescale of the mixing process. Malinie et al. (1993) claim that due to chemical inhomogeneities in the disk, re-mixing and star formation may be delayed by 10^{8-9} yr. We will include the consideration of delayed mixing in our calculations and inspect the influence of different mixing timescales on the observational constraints discussed above.

5.4.1 The two gas phases

We distinguish between two different phases of the gas component: the *active* and the *inactive* phase. The *inactive* gas

consists of the enriched stellar ejecta. Since this component is hot and not homogeneously distributed, stars cannot form out of this phase. The *active* phase, instead, is assumed to be cool and well mixed, hence, star formation is possible only in the *active* gas phase. In order to keep the circle of star formation and chemical enrichment alive, the *inactive* phase converts to the *active* star forming phase on a certain timescale, which includes both the *cooling* and the *mixing* process. The timescale is treated as a free parameter in the simulations.

To include this scenario in the calculations, we modify the equations 3 and 7 presented in section 2:

$$dM_g^{\text{inactive}}/dt = E - \frac{1}{\tau_{\text{mix}}} M_g^{\text{inactive}} \quad (21)$$

$$dM_g^{\text{active}}/dt = -\psi + f + \frac{1}{\tau_{\text{mix}}} M_g^{\text{inactive}} \quad (22)$$

To keep the equations as simple as possible, we assume the mass flow between the two gas phases to be proportional to the total amount of *inactive* gas divided by the mixing timescale. We now have to distinguish between the abundance in the *active* and the abundance in the *inactive* gas phase.

$$M_g^{\text{inactive}} dX_i^{\text{inactive}}/dt = E_i - X_i^{\text{inactive}} E \quad (23)$$

$$M_g^{\text{active}} dX_i^{\text{active}}/dt =$$

$$(X_i^{\text{inactive}} - X_i^{\text{active}}) \frac{1}{\tau_{\text{mix}}} M_g^{\text{inactive}} + (X_{i,f} - X_i^{\text{active}}) f \quad (24)$$

The SFR described by the Schmidt-law is then dependent on the density of the *active* gas:

$$\psi = \nu M_{\text{tot}} \left[\frac{M_g^{\text{active}}}{M_{\text{tot}}} \right]^k \quad (25)$$

The infalling material is assumed to mix instantaneously with the *active* gas.

5.4.2 Observational constraints

We now show the influence of the different mixing timescales on the observational constraints discussed in the previous subsections. The values of the parameters in table 7 are not changed.

5.4.2.1 [Mg/Fe] in metal-poor stars Figure 17 shows the results for mixing time scales of 0.01, 0.1, and 1 Gyr in the $[\text{Mg}/\text{Fe}]$ - $[\text{Fe}/\text{H}]$ diagram. Since the delay due to the mixing processes elongates the timescales (see upper x-axis for the case $\tau_{\text{mix}} = 0.1$ Gyr), the curve becomes flatter. The effect is maximum at early epochs and becomes negligible at solar ages.

The figure additionally shows the results for the inclusion of the enrichment due to 70 M_{\odot} -stars and delayed mixing (TNH96-yields, $\tau_{\text{mix}} = 0.1$ Gyr, long-dashed line).

5.4.2.2 AMR While the fit to the data in the $[\text{Mg}/\text{Fe}]$ - $[\text{Fe}/\text{H}]$ diagram has become better, the constraint on the AMR relation is still fulfilled. Even the results for mixing timescales of the order 10^9 Gyr are still in agreement with observations.

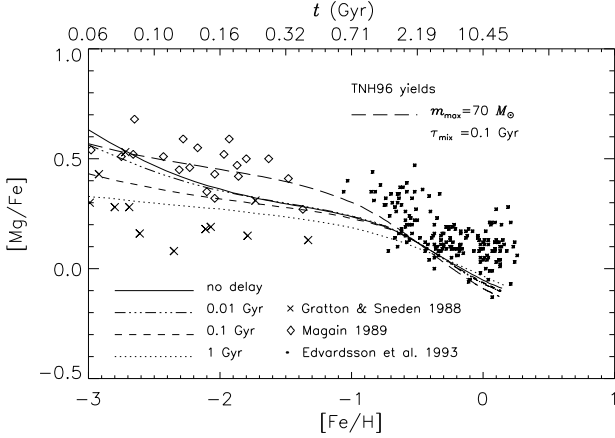


Figure 17. The abundance ratio $[Mg/Fe]$ as a function of $[Fe/H]$. For a detailed description see caption of figure 15. In these calculations, we relax the assumption of the IMA and consider different timescales for the mixing of the stellar ejecta with the ISM. SN II yields of TNH96 are used. The upper x-axis gives the progression of time for the case $\tau_{\text{mix}} = 0.1$ Gyr. The more the mixing is delayed, the flatter the curve becomes. The approximately constant value (there might be a slight decrease) of $[Mg/Fe]$ in metal-poor stars between $-3 \leq [Mg/Fe] \leq -1$ can be better reproduced when a delay in the mixing is assumed. The long-dashed line shows the result for $m_{\text{max}} = 70 M_{\odot}$ and $\tau_{\text{mix}} = 0.1$ Gyr.

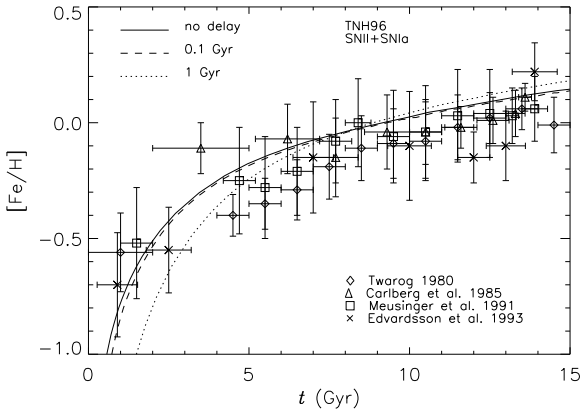


Figure 18. The age-metallicity relation (AMR) for the solar neighbourhood. For a detailed description see figure 13. The different lines show the influence of the different mixing timescales on the AMR relation. For timescales of the order 0.1 Gyr, the delayed mixing only affects the results at small t . In particular, the reproduction of the solar element abundances at $t = 10.45$ Gyr is not violated.

5.4.2.3 Solar element abundances Table 10 gives the element abundances in both gas phases for different mixing timescales. Since the sun forms out of *active* gas at $t = 10.45$ Gyr, these abundances have to match the solar values given by observation (table 8). The abundances in the *inactive* gas are systematically higher. The numbers show that the abundances of the elements H, O, and Z are well reproduced for the same set of parameters given in table 7, especially for $\tau_{\text{mix}} \leq 0.1$ Gyr

Since for a larger delay in the mixing, at the end less

Table 10. Same as table 8 for the two different gas phases and various mixing timescales. Stellar yields are taken from TNH96. The gas fractions give the fractions of *active* and *inactive* gas to the total mass at $t = 15$ Gyr. The element abundances of the *active* and *inactive* gas phases are given for $t = 10.45$ Gyr (birth of the sun). For a comparison with solar element abundances, the *active* gas phase has to be considered. The abundances in the *inactive* gas are systematically higher.

| τ_{mix} | 0.01 Gyr | 0.1 Gyr | 1 Gyr |
|--|----------|----------|----------|
| $M_g^{\text{active}}/M_{\text{tot}}(t_{\text{now}})$ | 1.30(−1) | 1.30(−1) | 1.35(−1) |
| $M_g^{\text{inactive}}/M_{\text{tot}}(t_{\text{now}})$ | 6.55(−5) | 6.70(−4) | 8.38(−3) |
| Z^{active} | 1.88(−2) | 1.91(−2) | 2.08(−2) |
| Z^{inactive} | 5.70(−2) | 5.73(−2) | 5.85(−2) |
| H^{active} | 6.98(−1) | 6.97(−1) | 6.92(−1) |
| H^{inactive} | 5.70(−1) | 5.70(−1) | 5.67(−1) |
| O^{active} | 9.43(−3) | 9.58(−3) | 1.05(−2) |
| O^{inactive} | 2.86(−2) | 2.88(−2) | 2.96(−2) |
| Mg^{active} | 4.57(−4) | 4.64(−4) | 5.17(−4) |
| Mg^{inactive} | 1.34(−3) | 1.35(−3) | 1.41(−3) |
| Fe^{active} | 1.23(−3) | 1.25(−3) | 1.32(−3) |
| Fe^{inactive} | 3.93(−3) | 3.93(−3) | 3.87(−3) |

gas is formed into stars, the fractions of both gas phases increase. However, more metal-poor stars are formed in the beginning. As a consequence, the element abundances at $t \gg \tau_{\text{mix}}$ (i.e. when the sun is born) become higher with increasing τ_{mix} . At $t \approx \tau_{\text{mix}}$, instead, a larger delay causes lower abundances in the ISM. For the case of the iron abundance, this pattern is demonstrated in figure 18.

5.4.2.4 ADF The formation of more low-metallicity stars, though, has consequences for the derived ADF. The discussion in section 5.2.1 showed that the adopted infall-model cannot fit the ADF in the whole metallicity range. At both ends of low and high metallicity, too many stars are formed. Certainly, the inclusion of delayed mixing worsens the situation. Figure 19 shows the results for the different mixing timescales.

There is no doubt, that the consideration of delayed mixing processes in the disk gives a more realistic approach to the chemical evolution in the solar neighbourhood (Schmidt 1963; Tinsley 1975). Since the formation of more metal-poor stars can hardly be avoided with a delayed mixing, the additional consideration of pre-enrichment of the disk due to early halo evolution (Burkert, Truran, & Hensler 1992) is necessary to solve the G-dwarf problem. However, to treat this scenario properly, more sophisticated evolution models, calculating halo and disk evolution separately, have to be considered.

6 CONCLUSION

Using two different sets of models for SN II yields (WW95 and TNH96), we analysed the influence of stellar nucleosynthesis on the chemical evolution of galaxies, in particular the element abundances in the solar neighbourhood.

It turns out that there is a good agreement in the SN II yields of oxygen and total metallicity between WW95 and TNH96 over the whole mass range of SN II. However,

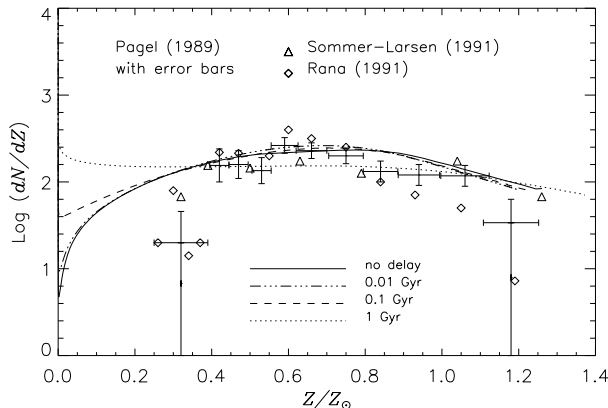


Figure 19. The abundance distribution function (ADF) giving the number of stars that are born per unit metallicity $\log(dN/dZ)$ as a function of metallicity. For a detailed descriptions see figure 11. The set of parameters is given in table 8. The different linestyles show the results for different mixing timescales. The larger the delay in the mixing processes, the more metal-poor stars form. The agreement with the observational data becomes worse. The consideration of pre-enrichment may be necessary.

from the point of view of galactic chemical evolution, there are significant differences in the magnesium yields in the mass range $18 - 25 M_{\odot}$. For a $20 M_{\odot}$ -star, the Mg-yield calculated by TNH96 is ~ 5 times higher than the result of WW95. We showed that, since the IMF is giving more weight to smaller masses, the results of chemical evolution models are very sensitive to this discrepancy. The iron yield, instead, is mainly uncertain in the upper mass range. WW95 and TNH96 agree very well in the lower mass range ($13 M_{\odot} \leq m \leq 20 M_{\odot}$) which is well constrained by the observed lightcurves of SN II events (SN1987A, SN1991J). However, in high mass stars with $m \geq 25 M_{\odot}$, WW95 models give significantly higher Fe-yields than TNH96. In total, this leads to lower $[\text{Mg}/\text{Fe}]$ -ratios produced by WW95-nucleosynthesis. A significantly super-solar value is only reached in high mass stars (figure 4) which are dominating the enrichment in the first few 10^7 yr of chemical evolution.

Only 0.04 Gyr after the birth of the first stars, the complete generation of SN II-exploding stars in the mass range $8 - 40 M_{\odot}$ is enriching the ISM. We calculated the SN II SSP-yields of O, Mg, and Fe for different IMF slopes and both nucleosynthesis prescriptions. The result is that TNH96-nucleosynthesis leads to $[\text{Mg}/\text{Fe}] = 0.26$ dex for Salpeter-IMF, while the ratio with WW95 (Z_{\odot} , model B) is 0.05 dex. We showed that this discrepancy is due to a lower Mg-SSP-yield of 0.13 dex and a higher Fe-SSP-yield of 0.08 dex in WW95. Even for a flat IMF with $x = 0.7$, the SSP-value of $[\text{Mg}/\text{Fe}]$ is 0.12 dex with WW95-yields. Without any impact from complex evolution models, from these numbers one can already conclude, that the $[\text{Mg}/\text{Fe}]$ overabundance in both, ellipticals and the solar neighbourhood, cannot be explained with the stellar yields of the WW95-models.

Applying the standard infall-model (Matteucci & Greggio 1986; Timmes et al. 1995; Yoshii et al. 1996) on the chemical evolution of the solar neighbourhood confirms the conclusions drawn from the discussion of the SSP yields.

Both, the $[\text{Mg}/\text{Fe}]$ overabundance in metal-poor stars and the magnesium abundance of the sun can be better reproduced with the Mg-yields of TNH96. In addition to this, we discussed the relaxation of the instantaneous *mixing* approximation for the chemical evolution in the solar neighbourhood. For this purpose, we modified the basic equations of chemical evolution separating the gaseous component into two different gas phases. While the *inactive* phase is enriched by the stellar ejecta, stars can only form out of the *active*, well mixed phase. A mass flow from the *inactive* to the *active* gas phase on a variable timescale represents the mixing process. For different mixing timescales of the order $10^7, 10^8, 10^9$ yr, we investigated the influence of a delayed mixing on the reproduction of the observational features. It turns out that a delay in the mixing supports the approximately constant value of $[\text{Mg}/\text{Fe}]$ in the $[\text{Mg}/\text{Fe}]-[\text{Fe}/\text{H}]$ -diagram in the low-metallicity range, while the agreement with the age-metallicity relation (AMR) and solar element abundances is not violated. However, since a delayed mixing causes the formation of more low-metallicity stars, the abundance distribution function (ADF) is less well reproduced. On the other hand, the instantaneous mixing of the stellar ejecta is certainly an unrealistic assumption, and the inclusion of a delay is a necessary step to improve chemical evolution models. Hence, the solution of the G-dwarf problem in the solar neighbourhood may require a combination of infall and pre-enrichment.

Since TNH96 include the $70 M_{\odot}$ -star in their computations, we additionally investigated the influence of a variation of the upper mass cutoff on the theoretical SSP-yields and on the chemical evolution in the solar neighbourhood. Applying TNH96 nucleosynthesis, the $[\text{Mg}/\text{Fe}]$ ratio in the ejecta of one SSP is significantly increased. This result is highly uncertain, however, because TNH96 do not consider fall back, which may play an important role for the nucleosynthetic contribution from high mass stars. Indeed, extrapolating the results of WW95 to $70 M_{\odot}$ leaves the SSP yields basically unchanged. The problem of the underestimation of the solar magnesium abundance remains the same also for TNH96-yields, since the Mg/O ratio in stars more massive than $40 M_{\odot}$ is even smaller. However, it is important to investigate quantitatively the metal contribution of stars more massive than $40 M_{\odot}$, since they could play an important role for chemical evolution.

In general, we demonstrated the sensitivity of galactic chemical evolution on nucleosynthesis prescriptions of type II supernovae. Different stellar yields can significantly alter conclusions on the parameters of chemical evolution models like IMF slope or star formation timescales. As long as the stellar nucleosynthesis of important elements like magnesium and iron is affected by so many uncertainties, the results from simulations of chemical evolution have to be interpreted considering the whole range of up to date nucleosynthesis calculations.

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APPENDIX A: IMF WEIGHTED YIELDS

The figures show the relative contribution of a $1 M_{\odot}$ mass interval to the total SN II yields of the elements oxygen, magnesium, iron, and metallicity for different IMF slopes and nucleosynthesis prescriptions (WW95, TNH96). The three

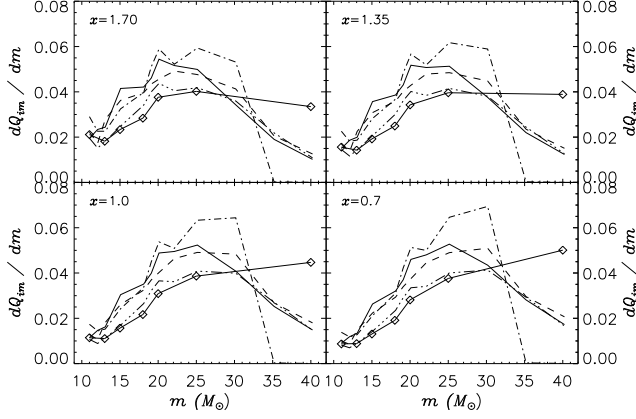


Figure A1. Oxygen. Model A.

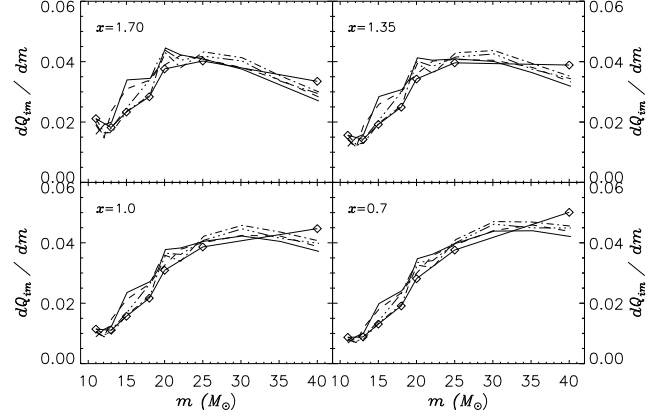


Figure A3. Oxygen. Model C.

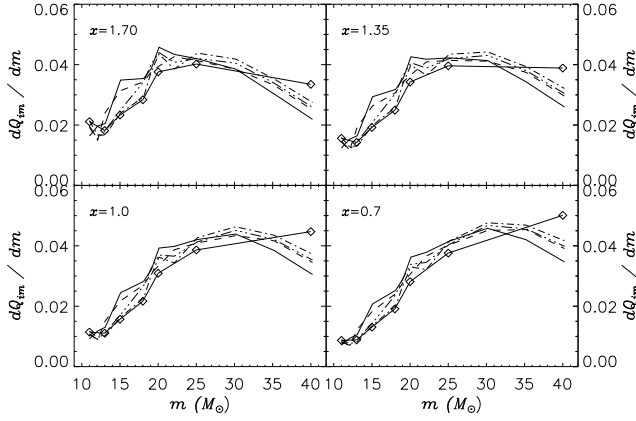


Figure A2. Oxygen. Model B.

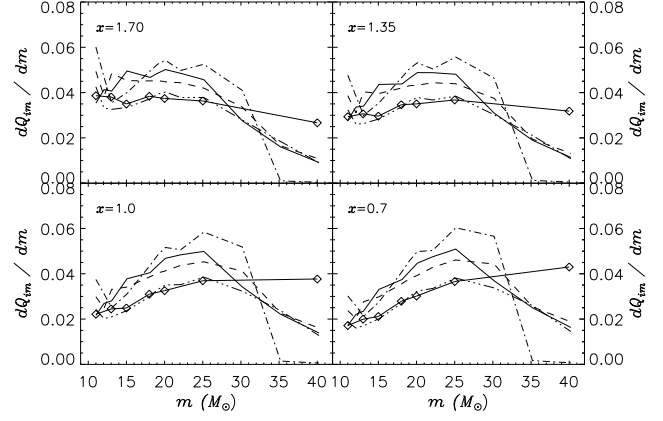


Figure A4. Metallicity. Model A.

models of different explosion energies (A,B,C)^{††} and four different initial metallicities ($10^{-4}Z_{\odot}$, $0.01Z_{\odot}$, $0.1Z_{\odot}$, Z_{\odot}) in WW95 are considered. Each figure shows the results for one certain element and one specified WW95-model (A,B,C). The four panels of each figure show the results for the four different IMF slopes. The four different initial metallicities of WW95 and TNH96-yields are plotted together in each panel. The meaning of the linestyles and symbols are specified in figure 1. The quantity dQ_{im}/dm is determined according to equation 17. It is normalized such that the integration over the total mass range of SN II ($11 - 40 M_{\odot}$) is equal 1. The x-axis give the initial stellar mass on the main sequence. To obtain the fractional contribution of a mass interval, one has to multiply the width of the interval (M_{\odot}) with the mean value of dQ_{im}/dm in this mass range.

A1 Oxygen

A2 Metallicity

A3 Magnesium

A4 Iron

^{††} See also table 2.

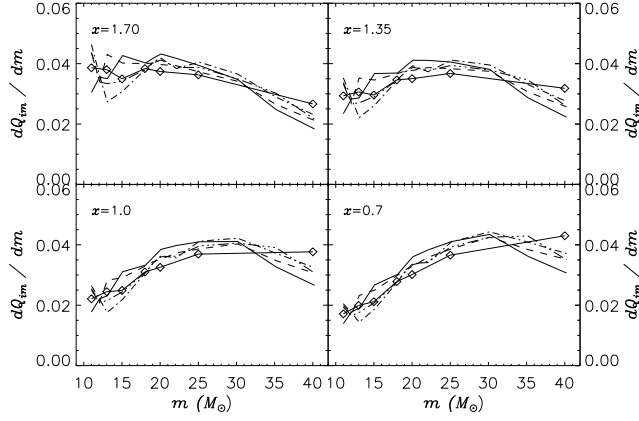


Figure A5. Metallicity. Model B.

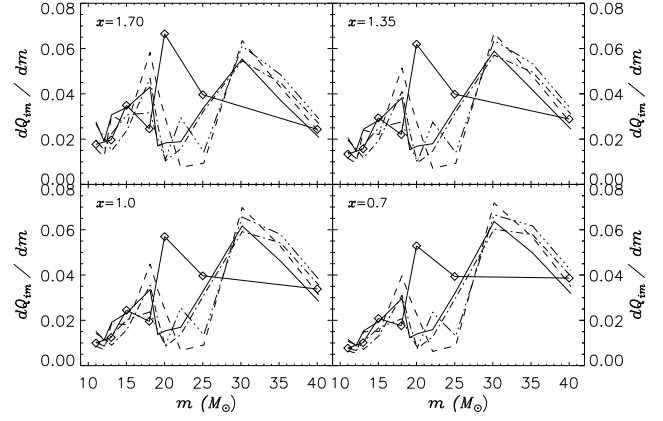


Figure A8. Magnesium. Model B.

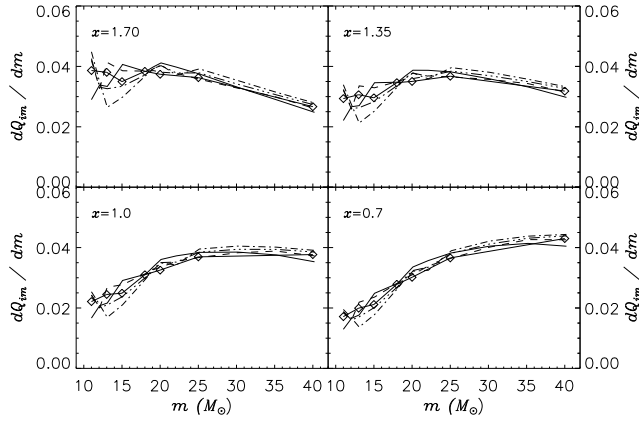


Figure A6. Metallicity. Model C.

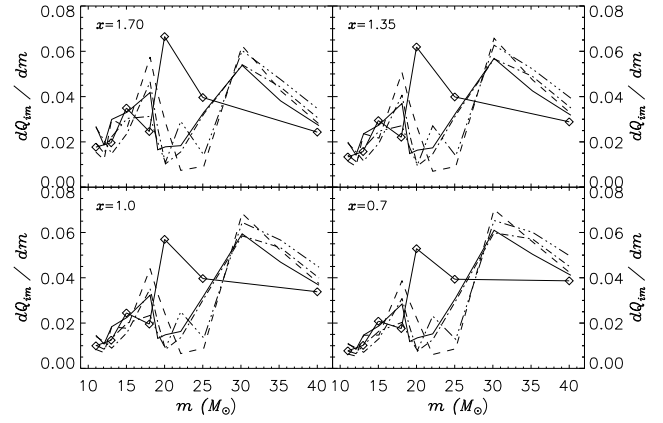


Figure A9. Magnesium. Model C.

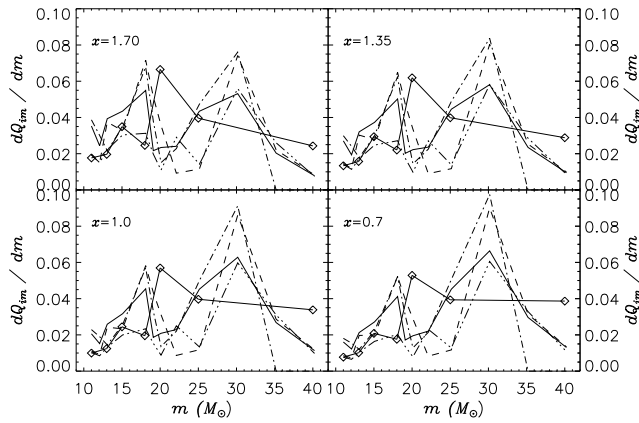


Figure A7. Magnesium. Model A.

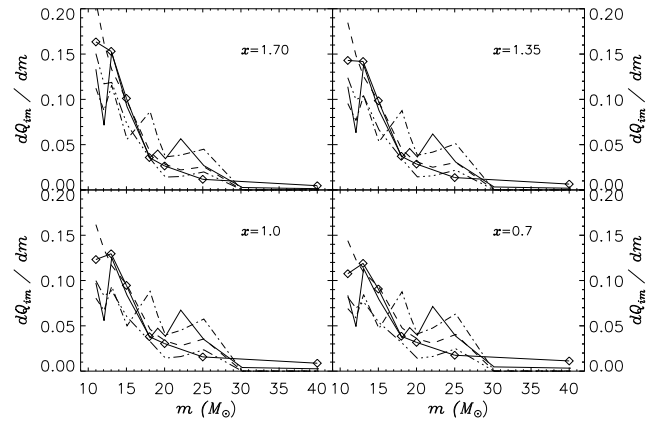


Figure A10. Iron. Model A.

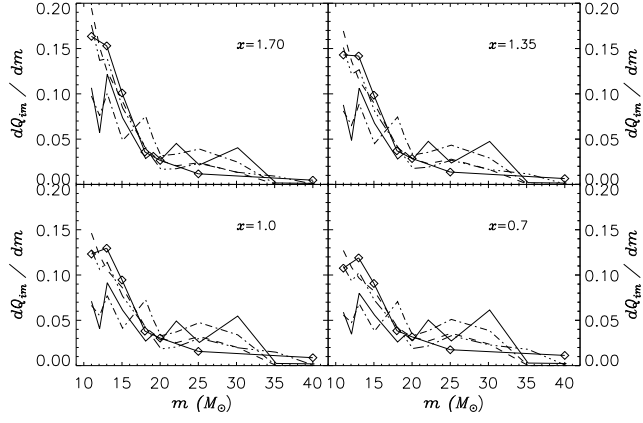


Figure A11. Iron. Model B.

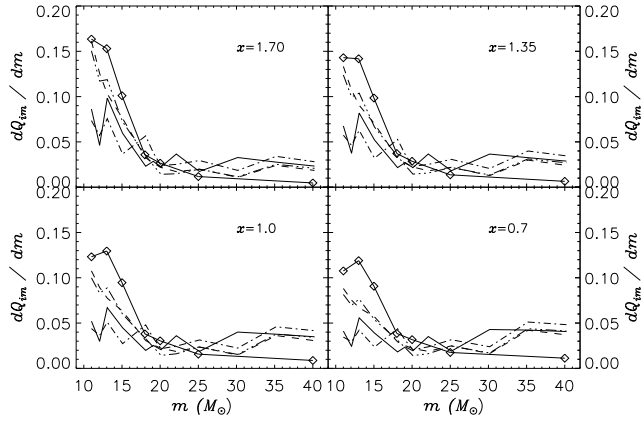


Figure A12. Iron. Model C.

APPENDIX B: SSP-YIELDS

The tables B1 to B12 show the abundances of oxygen, magnesium and iron in the ejecta of one generation of SN II-exploding stars (SSP-yields). One table refers to a certain IMF-slope and explosion model of WW95 (A,B,C). The values are normalized on (meteoritic) solar abundances from Anders & Grevesse (1989) and expressed on a logarithmic scale.

B1 $x = 1.7$

B2 $x = 1.35$

B3 $x = 1.0$

B4 $x = 0.7$

This paper has been produced using the Royal Astronomical Society/Blackwell Science L^AT_EX style file.

Table B1. WW95-model: A. IMF: $x = 1.70$.

| | TNH96 | WW95 ($0Z_{\odot}$) | WW95 ($10^{-4}Z_{\odot}$) | WW95 ($0.01Z_{\odot}$) | WW95 ($0.1Z_{\odot}$) | WW95 (Z_{\odot}) |
|---------|-------|--------------------------|--------------------------------|-----------------------------|----------------------------|-------------------------|
| [O] | 0.85 | 0.04 | 0.61 | 0.72 | 0.73 | 0.76 |
| [Mg] | 0.85 | 0.12 | 0.52 | 0.56 | 0.64 | 0.60 |
| [Fe] | 0.65 | 0.52 | 0.51 | 0.71 | 0.76 | 0.61 |
| [O/Fe] | 0.19 | -0.48 | 0.10 | 0.00 | -0.03 | 0.15 |
| [Mg/Fe] | 0.19 | -0.40 | 0.01 | -0.15 | -0.12 | -0.01 |

Table B2. WW95-model: B. IMF: $x = 1.70$.

| | TNH96 | WW95 ($0Z_{\odot}$) | WW95 ($10^{-4}Z_{\odot}$) | WW95 ($0.01Z_{\odot}$) | WW95 ($0.1Z_{\odot}$) | WW95 (Z_{\odot}) |
|---------|-------|--------------------------|--------------------------------|-----------------------------|----------------------------|-------------------------|
| [O] | 0.85 | 0.43 | 0.75 | 0.77 | 0.79 | 0.83 |
| [Mg] | 0.85 | 0.44 | 0.68 | 0.65 | 0.73 | 0.71 |
| [Fe] | 0.65 | 0.68 | 0.57 | 0.76 | 0.79 | 0.70 |
| [O/Fe] | 0.19 | -0.26 | 0.17 | 0.01 | 0.00 | 0.13 |
| [Mg/Fe] | 0.19 | -0.25 | 0.11 | -0.11 | -0.06 | 0.00 |

Table B3. WW95-model: C. IMF: $x = 1.70$.

| | TNH96 | WW95 ($0Z_{\odot}$) | WW95 ($10^{-4}Z_{\odot}$) | WW95 ($0.01Z_{\odot}$) | WW95 ($0.1Z_{\odot}$) | WW95 (Z_{\odot}) |
|---------|-------|--------------------------|--------------------------------|-----------------------------|----------------------------|-------------------------|
| [O] | 0.85 | 0.66 | 0.75 | 0.78 | 0.80 | 0.85 |
| [Mg] | 0.85 | 0.63 | 0.69 | 0.66 | 0.73 | 0.72 |
| [Fe] | 0.65 | 0.78 | 0.70 | 0.83 | 0.87 | 0.80 |
| [O/Fe] | 0.19 | -0.12 | 0.06 | -0.06 | -0.07 | 0.05 |
| [Mg/Fe] | 0.19 | -0.15 | -0.01 | -0.17 | -0.14 | -0.08 |

Table B4. WW95-model: A. IMF: $x = 1.35$.

| | TNH96 | WW95 ($0Z_{\odot}$) | WW95 ($10^{-4}Z_{\odot}$) | WW95 ($0.01Z_{\odot}$) | WW95 ($0.1Z_{\odot}$) | WW95 (Z_{\odot}) |
|---------|-------|--------------------------|--------------------------------|-----------------------------|----------------------------|-------------------------|
| [O] | 0.92 | 0.05 | 0.66 | 0.78 | 0.79 | 0.81 |
| [Mg] | 0.91 | 0.13 | 0.57 | 0.63 | 0.69 | 0.66 |
| [Fe] | 0.65 | 0.50 | 0.52 | 0.70 | 0.75 | 0.62 |
| [O/Fe] | 0.26 | -0.45 | 0.14 | 0.07 | 0.04 | 0.20 |
| [Mg/Fe] | 0.26 | -0.37 | 0.05 | -0.08 | -0.05 | 0.04 |

Table B5. WW95-model: B. IMF: $x = 1.35$.

| | TNH96 | WW95 ($0Z_{\odot}$) | WW95 ($10^{-4}Z_{\odot}$) | WW95 ($0.01Z_{\odot}$) | WW95 ($0.1Z_{\odot}$) | WW95 (Z_{\odot}) |
|---------|-------|--------------------------|--------------------------------|-----------------------------|----------------------------|-------------------------|
| [O] | 0.92 | 0.49 | 0.82 | 0.84 | 0.86 | 0.90 |
| [Mg] | 0.91 | 0.49 | 0.76 | 0.73 | 0.80 | 0.78 |
| [Fe] | 0.65 | 0.70 | 0.59 | 0.77 | 0.79 | 0.73 |
| [O/Fe] | 0.26 | -0.21 | 0.22 | 0.07 | 0.07 | 0.17 |
| [Mg/Fe] | 0.26 | -0.21 | 0.16 | -0.04 | 0.01 | 0.05 |

Table B6. WW95-model: C. IMF: $x = 1.35$.

| | TNH96 | WW95 ($0Z_{\odot}$) | WW95 ($10^{-4}Z_{\odot}$) | WW95 ($0.01Z_{\odot}$) | WW95 ($0.1Z_{\odot}$) | WW95 (Z_{\odot}) |
|---------|-------|--------------------------|--------------------------------|-----------------------------|----------------------------|-------------------------|
| [O] | 0.92 | 0.74 | 0.82 | 0.84 | 0.86 | 0.91 |
| [Mg] | 0.91 | 0.70 | 0.76 | 0.74 | 0.80 | 0.79 |
| [Fe] | 0.65 | 0.82 | 0.74 | 0.86 | 0.89 | 0.84 |
| [O/Fe] | 0.26 | -0.08 | 0.08 | -0.01 | -0.03 | 0.07 |
| [Mg/Fe] | 0.26 | -0.12 | 0.02 | -0.12 | -0.09 | -0.05 |

Table B7. WW95-model: A. IMF: $x = 1.00$.

| | TNH96 | WW95 ($0Z_{\odot}$) | WW95 ($10^{-4}Z_{\odot}$) | WW95 ($0.01Z_{\odot}$) | WW95 ($0.1Z_{\odot}$) | WW95 (Z_{\odot}) |
|---------|-------|--------------------------|--------------------------------|-----------------------------|----------------------------|-------------------------|
| [O] | 0.98 | 0.07 | 0.71 | 0.83 | 0.84 | 0.86 |
| [Mg] | 0.97 | 0.13 | 0.62 | 0.69 | 0.75 | 0.71 |
| [Fe] | 0.65 | 0.47 | 0.53 | 0.69 | 0.74 | 0.62 |
| [O/Fe] | 0.33 | -0.41 | 0.18 | 0.14 | 0.10 | 0.24 |
| [Mg/Fe] | 0.32 | -0.35 | 0.09 | 0.00 | 0.01 | 0.09 |

Table B8. WW95-model: B. IMF: $x = 1.00$.

| | TNH96 | WW95 ($0Z_{\odot}$) | WW95 ($10^{-4}Z_{\odot}$) | WW95 ($0.01Z_{\odot}$) | WW95 ($0.1Z_{\odot}$) | WW95 (Z_{\odot}) |
|---------|-------|--------------------------|--------------------------------|-----------------------------|----------------------------|-------------------------|
| [O] | 0.98 | 0.55 | 0.88 | 0.90 | 0.92 | 0.95 |
| [Mg] | 0.97 | 0.54 | 0.82 | 0.80 | 0.86 | 0.84 |
| [Fe] | 0.65 | 0.71 | 0.61 | 0.77 | 0.78 | 0.75 |
| [O/Fe] | 0.33 | -0.16 | 0.27 | 0.13 | 0.13 | 0.20 |
| [Mg/Fe] | 0.32 | -0.17 | 0.21 | 0.03 | 0.08 | 0.09 |

Table B9. WW95-model: C. IMF: $x = 1.00$.

| | TNH96 | WW95 ($0Z_{\odot}$) | WW95 ($10^{-4}Z_{\odot}$) | WW95 ($0.01Z_{\odot}$) | WW95 ($0.1Z_{\odot}$) | WW95 (Z_{\odot}) |
|---------|-------|--------------------------|--------------------------------|-----------------------------|----------------------------|-------------------------|
| [O] | 0.98 | 0.81 | 0.89 | 0.91 | 0.92 | 0.97 |
| [Mg] | 0.97 | 0.77 | 0.83 | 0.81 | 0.87 | 0.85 |
| [Fe] | 0.65 | 0.86 | 0.79 | 0.88 | 0.91 | 0.89 |
| [O/Fe] | 0.33 | -0.05 | 0.10 | 0.03 | 0.01 | 0.08 |
| [Mg/Fe] | 0.32 | -0.09 | 0.04 | -0.07 | -0.04 | -0.03 |

Table B10. WW95-model: A. IMF: $x = 0.70$.

| | TNH96 | WW95 ($0Z_{\odot}$) | WW95 ($10^{-4}Z_{\odot}$) | WW95 ($0.01Z_{\odot}$) | WW95 ($0.1Z_{\odot}$) | WW95 (Z_{\odot}) |
|---------|-------|--------------------------|--------------------------------|-----------------------------|----------------------------|-------------------------|
| [O] | 1.03 | 0.07 | 0.74 | 0.87 | 0.88 | 0.89 |
| [Mg] | 1.01 | 0.12 | 0.65 | 0.73 | 0.79 | 0.74 |
| [Fe] | 0.64 | 0.45 | 0.52 | 0.67 | 0.72 | 0.61 |
| [O/Fe] | 0.39 | -0.38 | 0.21 | 0.20 | 0.16 | 0.28 |
| [Mg/Fe] | 0.37 | -0.32 | 0.13 | 0.06 | 0.07 | 0.13 |

Table B11. WW95-model: B. IMF: $x = 0.70$.

| | TNH96 | WW95 ($0Z_{\odot}$) | WW95 ($10^{-4}Z_{\odot}$) | WW95 ($0.01Z_{\odot}$) | WW95 ($0.1Z_{\odot}$) | WW95 (Z_{\odot}) |
|---------|-------|--------------------------|--------------------------------|-----------------------------|----------------------------|-------------------------|
| [O] | 1.03 | 0.60 | 0.93 | 0.95 | 0.96 | 1.00 |
| [Mg] | 1.01 | 0.58 | 0.88 | 0.86 | 0.91 | 0.89 |
| [Fe] | 0.64 | 0.72 | 0.62 | 0.77 | 0.77 | 0.76 |
| [O/Fe] | 0.39 | −0.12 | 0.31 | 0.18 | 0.19 | 0.23 |
| [Mg/Fe] | 0.37 | −0.14 | 0.26 | 0.09 | 0.14 | 0.12 |

Table B12. WW95-model: C. IMF: $x = 0.70$.

| | TNH96 | WW95 ($0Z_{\odot}$) | WW95 ($10^{-4}Z_{\odot}$) | WW95 ($0.01Z_{\odot}$) | WW95 ($0.1Z_{\odot}$) | WW95 (Z_{\odot}) |
|---------|-------|--------------------------|--------------------------------|-----------------------------|----------------------------|-------------------------|
| [O] | 1.03 | 0.87 | 0.94 | 0.95 | 0.97 | 1.02 |
| [Mg] | 1.01 | 0.82 | 0.88 | 0.86 | 0.92 | 0.90 |
| [Fe] | 0.64 | 0.89 | 0.83 | 0.90 | 0.93 | 0.92 |
| [O/Fe] | 0.39 | −0.02 | 0.11 | 0.05 | 0.04 | 0.10 |
| [Mg/Fe] | 0.37 | −0.07 | 0.06 | −0.04 | −0.01 | −0.01 |